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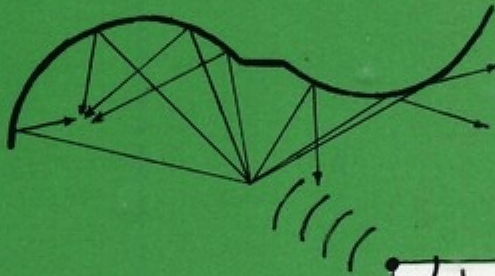
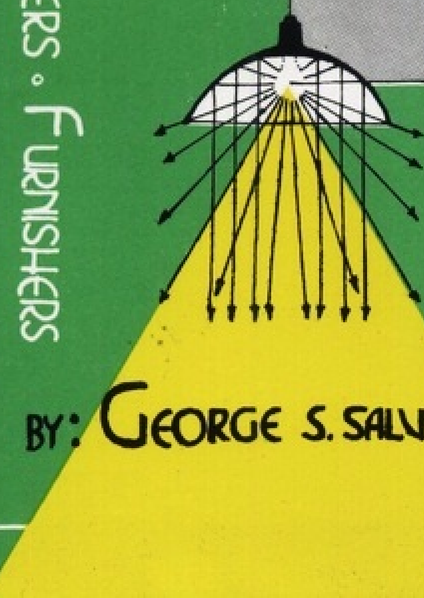
ARCHITECTURAL UTILITIES 3

LIGHTING AND ACOUSTICS





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BY: George S. Salvan

ARCHITECTURAL UTILITIES 3
LIGHTING AND ACOUSTICS

• THE NEW LADDER TYPE CURRICULUM

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Dedicated to all future
Architects and Engineers

The hope for a functional, comfortable
and convenient designs for better living.

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To the many students of architecture whose curiosity and interest in lighting and acoustics to be in a book form have been a source of inspiration.

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PREFACE

Architectural acoustics and lighting is an exact science and practical art. The architect who has a working knowledge of these subjects can plan adequately for the acoustics and lighting of the buildings he designs. It is the purpose of this book to present the working principles of this science and art in a simple, useful, and convenient form. Architectural designing based on these principles will assure the construction of rooms and buildings which are free from disturbing glare noises and which provide the optimum conditions for reading, producing and listening to either speech or music. Functional acoustical and lighting design demands scientific, aesthetic, and practical planning.

Acoustical designing in architecture begins with the preliminary sketches on the drafting board and continues throughout all stages of planning and construction. Good acoustics will be assured in the buildings an architect designs if he has an understanding of the technological principles of architectural acoustics and knows how to apply them.

For many years an artificial dichotomy existed in the field of lighting design, dividing it into two disciplines: architectural lighting and utilitarian design the former trend found expression in architectural building design that took little cognizance of vision needs, but that displayed an inordinate penchant for incandescent wall washers and architectural lighting elements while regarding the added-on utilitarian lighting with partially justified asperity. The latter,trend saw all spaces in terms of room or cavity ratios and designed lighting with foocandles and financial consideration (peso or dollar) as the ruling considerations. That both these trends have in large measure been eliminated is due in large measure to the work of the Illuminating Engineering Society (IES), and its members and new found energy consciousness that followed the 1973 arab oil Embargo. The latter spurred research into satisfying real vision need within a framework of minimal energy use, and convinced architects that in addition to seeing the building, it must be possible to see within the building. The architectural designer must then take cognizance of these factors:

1. The manifold ramifications of daylighting
2. The intimate interrelation between the energy aspects of artificial and natural lighting, heating and cooling.
3. The effect of lighting needs on interior space arrangement, for example, the desirability of grouping similar lighting requirement tasks.
4. The characteristics, means of generation, effects, and utilization techniques of artificial lighting.

As a result of the need to consider these and other interrelated factors, many of which are mutually incompatible, the architect is faced with many tread-off type decisions. The purpose of this book is then twofold: to provide the background that will help the architect make these decisions correctly and to make him or her proficient in the use of lighting as a design material.

This book is intended as a practical guide to good acoustical and lighting design in architecture. It is written primarily for architects, students of architecture, and all others who wish a non-mathematical but comprehensive treatise on this subjects. Useful design data have been presented in such a manner that the text can serve as a convenient handbook in the solution of most problems encountered in architectural acoustics and lighting.

This book is composed of two sections. The first section discusses about "Acoustics" and is further divided into two parts. The general principles and procedures on which all acoustical designing should be based considered in chapters 1 to 10 specific applications of these principles and procedures are described in chapter 11 these applications include the design of auditoriums, theatres, school buildings, commercial and public buildings, homes, apartments and hotels, churches, radio and television, sound-recording studios.

The second section discussed "LIGHTING" and is also further divided into two parts The general principles and procedures light sources on which all the lighting designing should be based are considered in chapters 12 to 15. Specific applications of these principles and procedures are described in chapter 16. These applications include the lighting applications on Residential occupancies, Institutional and Educational buildings, Commercial Interiors, Industrial lighting, and other Design Topics such as Automatic energy control, Emergency lighting, Building retrofit, Floodlighting and Streetlighting. A short discussion follows on Disco-lighting.

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PART 1 ACOUSTICS

1 FUNDAMENTALS OF ARCHITECTURAL ACOUSTICS

SOUND THEORY

General

Architectural acoustics may be defined as the technology of designing spaces, structures, and mechanical systems to meet hearing needs. With proper design, "wanted" sounds can be heard properly and "unwanted" sounds or "noise", can be attenuated to the point where it does not cause annoyance. However, achieving good acoustics has become increasingly more difficult for a variety of reasons. To cut costs, the weight of construction materials used in many of today's buildings is reduced. Since light structures generally transmit more sound than heavy ones, this practice poses major acoustical problems. Forty percent or more of a building budget may be allocated for mechanical systems-most of which makes noise. Outside noise sources such as cars, trucks, trains, and airplanes present problems in isolating interior spaces from exterior sound.

All acoustics situations have three common elements — source, transmission path, and receiver. The source can be made louder or quieter and the path can be made to transmit more or less sound. The listener's reception of sound also may be influenced.

What is Sound?

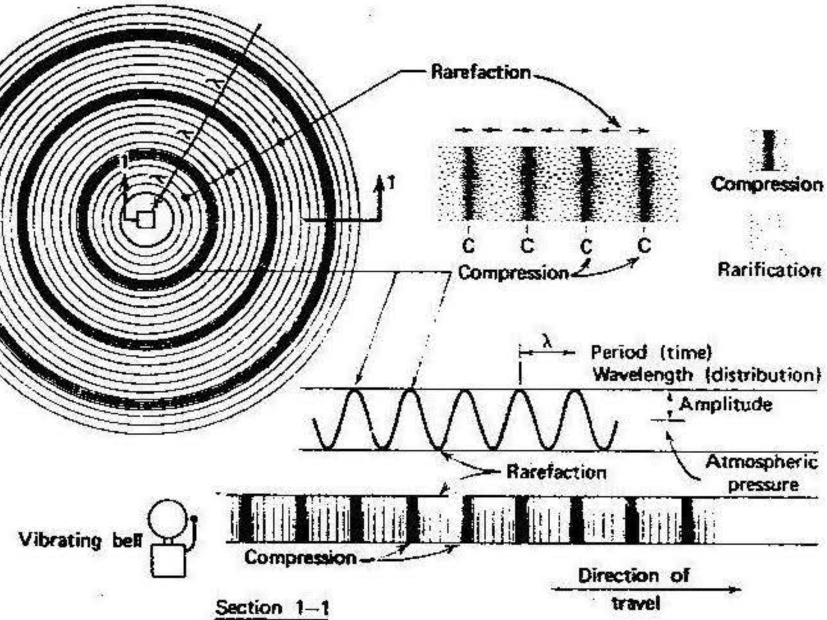
Sound is a physical wave, or a mechanical vibration, or simply a series of pressure variations, in an elastic medium. For airborne sound, the medium is air. For structure-borne sound the medium is concrete, steel, wood, glass and combinations of all of these.

For architects, we simply define sound as an **audible signal**. This does not mean that subsonic or supersonic signals are not sound, nor does it mean that we are taking a stand on the existential question of whether unheard sound exists. It simply means that the science of architectural acoustics is concerned with the building occupants, and sounds which he or she cannot detect are generally nor our concern.

To further clear the air, it is always assumed that the hearer has a pair of healthy young ears with a detection range of 20 to 20,000 Hz. With these givens, it is probably best to view sound as a series of pressure variations. In air, these pressure variations take the form of periodic compressions and rarefactions.

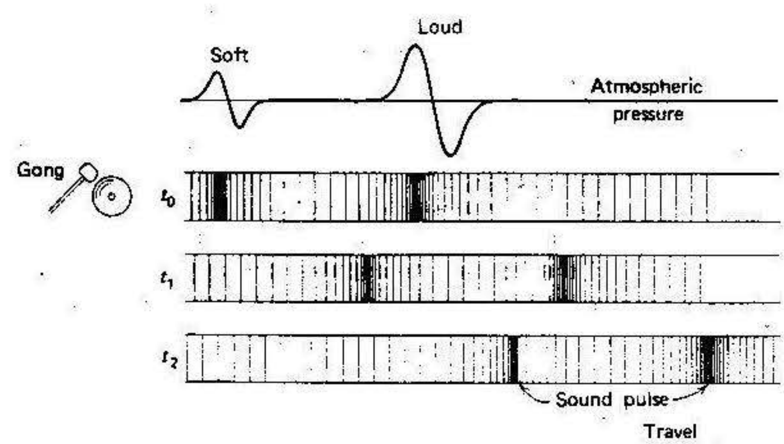
Figure of Sound Pressure Waves

(a)



(a) This is a continuous vibration that causes a series of compressions and rarefactions to travel outward longitudinally from the source. Amplitude information is carried by pressure, that is, greater amplitude means greater compression and greater rarefaction.

(b)



(b) Two single impulses of different magnitude (amplitude) are shown traveling away from the source. Note how amplitude information is carried by difference in pressure.

The bell radiates a pure tone in all directions equally, that is, it creates a pure tone in all directions equally, that is, it creates a circular wave front. As the bell vibrates it sets up vibrations in the air, of the same frequency, which can best be seen in the sectional view. Notice that the pressure changes containing the sound information travel in the same direction as the wave front-longitudinally. This is unlike a radio signal for instance in which the wave travels longitudinally but the information, that is, the wave height and shape, is transverse. Sound is therefore longitudinal mechanical wave motion.

Propagation of Sound

A falling tree generates sound. This is a *physical disturbance,* or an alteration or pulsation of pressure of being detected by a normal ear by traveling through air. In any case, a medium possesing inertia and elasticity is needed to propogate it. Sound waves do not travel through a vacuum.

The auditory sensation produced by sound waves will be called *sound sensation.* The crashing tree produces a sound sensation only when an ear hears it.

Sound has its origin in vibrating bodies. A plucked violin string or a struck tuning fork can actually be seen to vibrate. In the sounding board of a piano and the paper cone of a loud speaker, as in most other sound sources, the amplitude of vibration is too small to be observed visually but often the vibration can be felt with the finger tips, consider a body vibrating in air. As it moves in an outward direction, it pushes a "layer" of air along with it; this layer of air is compressed, and its density and temperature are correspondingly increased. Since the pressure of this layer is higher than that in the undisturbed surrounding atmoshpere, the particles (that is, the Molecules) in it tend to move in the outward direction and transmit their motion to the next layer, and so on. As the vibrating body moves inward, the layer of air adjacent to it is rarefied. This layer of rarefaction follows the layer of compression in the outward direction, and at the same speed; the succession of outwardly traveling layers of compression and rarefaction is called *wave motion.* The speed of propagation is determined by the compressibility and density of the medium-the less the compressibility of the medium and the less its density, the faster will the wave motion be propagated.

The changes in pressure, density, and temperature due to the passage of the sound wave through air are usually extremely small. For example, the effective sound pressure, the root-mean-square of the pressure variations, in the air 3 feet from a trumpet is about 9 dynes per square centimeter. This means that the pressure fluctuations are only about nine millionths of the normal atmospheric pressure, which is 1.01×10^6 dynes per square centimeter, or 14.7 pounds per square inch (see appendix for conversion factors of units)

Velocity of Propagation

Sound travels at different velocities depending upon the medium. In air, at sea level, sound velocity is 344 m/sec or 1130 fps. This corresponds to 770 miles per hour (mph) or 478 kilometers per hour (kmph) — slow indeed when compared to light at 186,000 miles per second. Since sound travels not only in air but also through parts of the structure it is of interest to know the velocities in other media. Sound travels much faster in liquids and solids than it does in air.

Sound Propagation Velocity in Various Media

	Velocity	
Medium	Meters per Second	Feet per Second
Air	344	1130
Water	1410	4625
Wood	3300	10,825
Brick	3600	11,800
Concrete	3700	12,100
Steel	4900	16,000
Glass	5000	16,400
Aluminum	5800	19,000
	at 22.2°C	at 72°F

Speed of Sound

As sound travels much slower than speed of light, the resulting defects in many rooms are echoes and reverberations. Experimental data show that when the reflected sounds which reach an observer are delayed more than about 0.058 second, relative to direct sounds, they are distinguished as echoes. (sound travels approximately 65 feet in this time interval.) Reverberation, as most simply interpreted, consists of successive reflections of a sound in a room, and since sound travels only about 1130 feet or 344 meters per second these usually will be a rather long succession of these reflections before the sound dies away to inaudibility.

Thus we see that the speed of sound plays a significant role in architectural acoustics.

For all practical purposes in architectural acoustics, the speed of sound is independent of frequency, intesity, and changes in atmoshperic pressure. Temperature does have a significant effect on the speed, increasing it about 1.1 feet or (3 centimeters) per second per degree Fahrenheit rise in temperature. The dependence of the speed of sound on temperature is one of the prime causes of the bending of sound rays in the atmosphere. This bending (refraction) of sound waves sometimes affects the distribution of sound reaching an audience, especially in open-air theatres.

The speed of sound in air is given by $\sqrt{1.40\ Ps/p}$

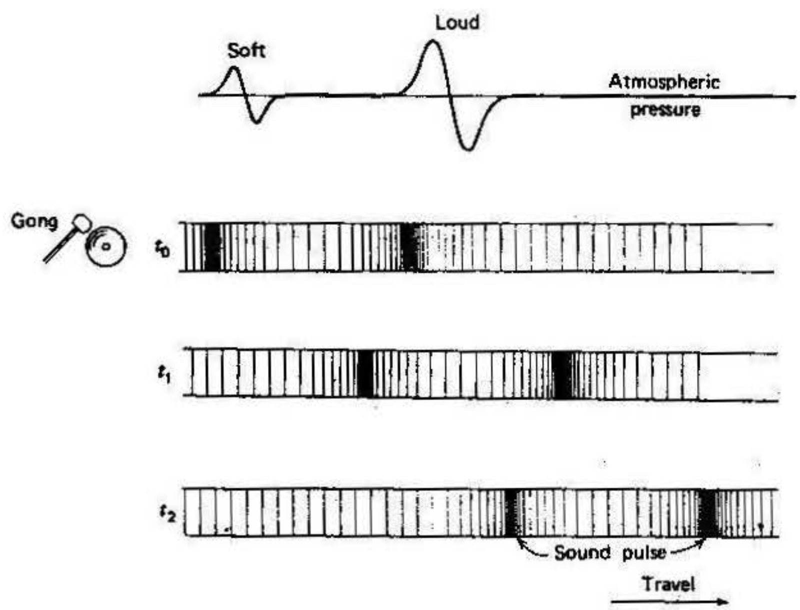
Ps = atmospheric pressure

ϱ = its density

The term *velocity of sound* is often used interchangeably with *speed of sound* although, strictly speaking, the two are not the same. *Velocity* includes both *speed* and *direction* of propagation; velocity is speed in a specified direction; that is velocity is a vector quantity. The direction of propagation is the direction of the advance of the wave, defined more accurately by the perpendicular to a *wave front* (surface of constant phase) of the advancing wave.

Frequency

The number of times the cycle of compression and rarefaction of air (or to and for vibrations that the source) makes in a given unit of time or 1 second is described as the *frequency* of a sound (or vibration). For example, if there are 1000 cycles in one second, the frequency of the sound is 1000 cps [1000 hertz (Hz) in the standard nomenclature]. Thus, in the figure higher frequencies would be shown by compressions and rarefactions that are closer together and lower frequencies by those that are further apart.



(b)

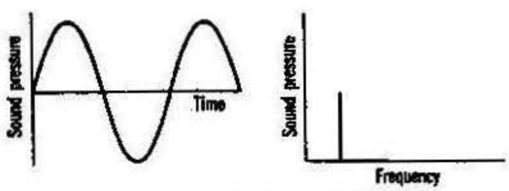
In sound, frequency is often referred to by a term borrowed from musical concepts — *pitch.* The higher the frequency the higher the pitch, and vice versa. As stated, the approximate frequency range of a healthy young person's hearing is 20 to 20,000 Hz. This upper limit decreases with age as a result of a process called presbycusis. Recognition of this phenomenon can be of importance to schools, since very high-pitched sounds that are inaudible to most adults, can be a source of extreme annoyance to students.

The human speaking voice has a range of approximately 100 to 600 Hz in fundamentals, but harmonics (overtones) reach to approximately 7500 Hz. Most speech information, is carried in the upper frequencies while most energy exists in the lower frequencies while most energy exists in the lower frequencies. The critical range of speech communication is 300 to 4000 Hz. Overtones outside these frequencies give the voice its characteristics sound and specific identity.

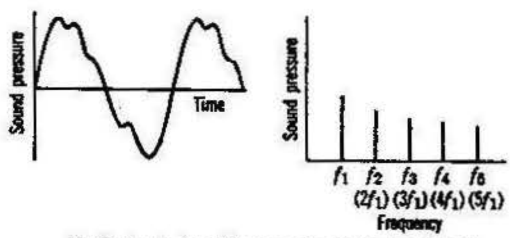
A sound composed on only one frequency is a pure tone. Except for the sound generated by a tuning fork, few sounds are truly pure. Musical sounds are composed of a fundamental frequency and integral multiples of the fundamental frequency (harmonics). Most common sounds are complex combinations of frequencies.

The source and the observer are at rest with respect to the medium — the usual assumption in room acoustics. Frequency is a physical phenomenon. It can be measured by instruments, and it is closely related to, but not the same as pitch — a psychological phenomenon. Frequency is usually designated by a number followed by *cycles per second* or CPS.

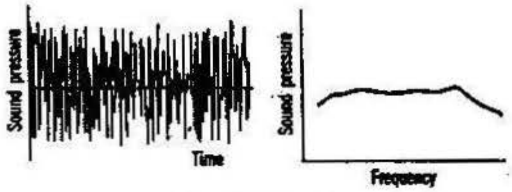
Most common sounds are complex combinations of frequencies. The figure below shows examples of pure tones, musical notes, and common sounds; (speech, music, and noise), showing the variation of sound pressure with time and frequency.



Tuning fork (pure tone)



Musical note (combination of several pure tones)



Speech, music, noise

The following figure shows the frequency ranges of some common devices and phenomena. The frequencies shown in the figure all stand in the ratio of 2:1 to each other, that is, 16:32:63:125:250 and so on. Borrowing again from musical terminology, they are one *octave* apart.

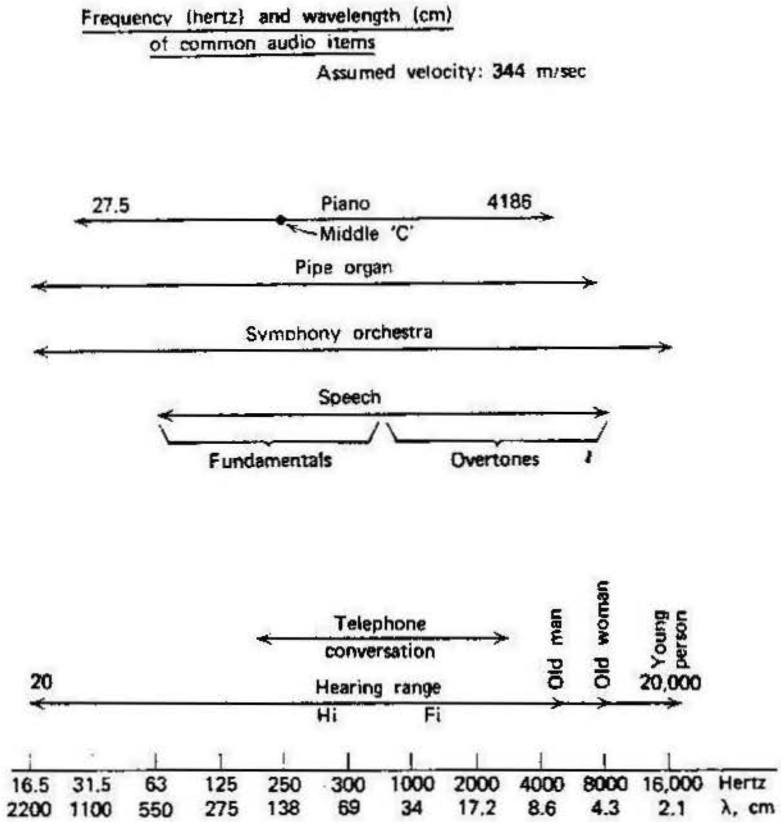


Figure of Frequency Ranges of Common Instruments.

Wavelength and Types of

Propagation

The wavelength of a sound may be defined as the distance between similar points on successive waves or the distance the sound travels in one cycle of vibration, That is, in *1/second,* is called its *wavelength* and is denoted by the Greek letter lambda λ. The relationship between wavelength, frequency, and velocity of a sound is expressed as

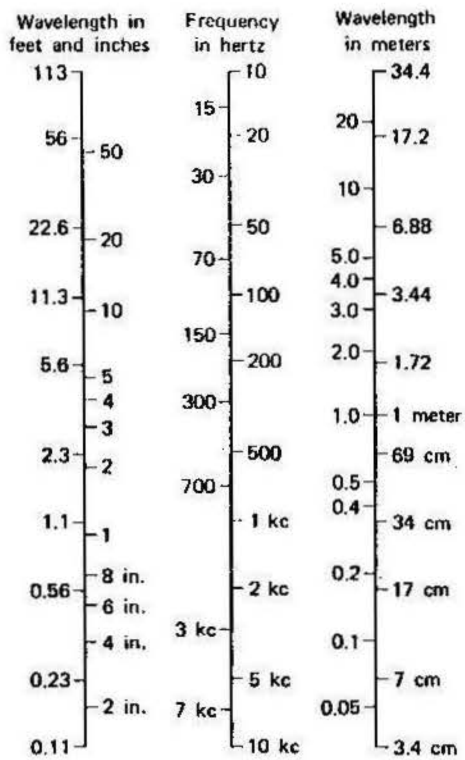
$$\lambda = \frac{C}{f} \quad \text{or} \quad \lambda f = C$$

where λ = wavelength, in ft or M

c = velocity of sound, in fps or min/sec

f = frequency of sound Hz

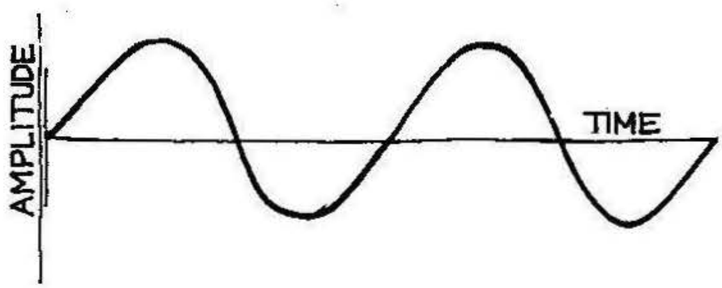
Low-frequency sounds are characterized by long wavelengths and high-frequency sounds by short wavelengths. Sounds with wavelengths ranging from ½ inch to 50 feet or 1.25 cm to 15.25 m can be heard by humans. A simple nomograph is shown in the figure, which permits rapid determination of wavelength given frequency, and vice versa.



Wave Form

The wave form of sound wave describes, by means of a graphical representation, the precise nature of a complete to and-fro oscillation of the vibrating particles in a sound field. Thus below is a graph of the simple harmonic *wave form* of the sound generated by a gently struck tuning fork; it gives as the function of the time the instantaneous displacement (plotted vertically) of a typical vibrating particle.

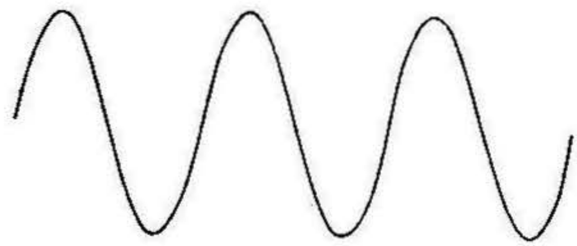
Sine Wave



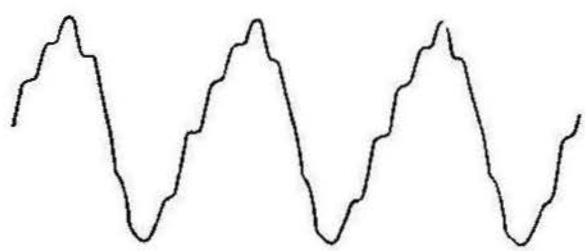
each complete cycle in the sine wave graph corresponds to a complete cycle of the tuning fork or of the sound wave it generates. Although the displacements are represented as transverse to the time axis, the actual displacements of the particles in the sound field are parallel to the direction of propagation of the sound wave, that is, the wave motion is longitudinal.

The wave forms of musical tones are somewhat more complicated. For example the next figure shows the wave forms of sustained tones produced by a tuning fork, a violin and an oboe. These records are for sustained musical tones of the same fundamental frequency and approximately the same amplitude of vibration. However, they differ markedly in their wave forms. Although not simple harmonic, the wave forms for these tones are periodic; they repeat at definite intervals. They are called complex waves in contradistinction to simple harmonic waves. It is possible, by mathematical or instrumental means, or both, to analyze complex wave forms, like those characteristic of the oboe or any other instrument, into a series of simple harmonic vibrations. Thus, a complex tone (or its graphical representation as a complex wave form) may be regarded as made up of a series os simple harmonic tones (or waves). Usually the frequencies of these component simple harmonic tones are integral multiples of the frequency of the fundamental component, which is sometimes referred to as the gravest component.

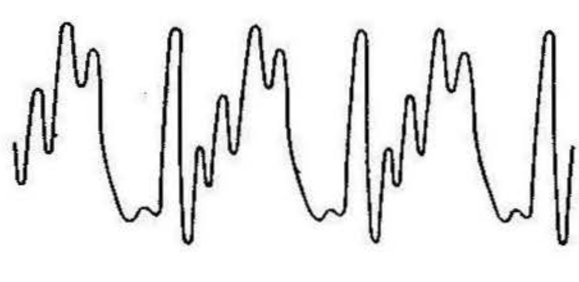
TUNING FORK



VIOLIN



OBOE

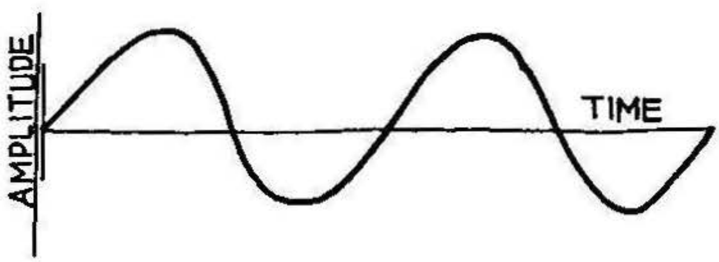


Sound Magnitude

When we speak of sound magnitude, we think of loudness, which is a subjective, ear-oriented reaction not linearly related to the physical quantity of sound. The level (quantity) of sound pressure, sound pressure level (SPL), sound intensity, and sound intensity level (IL), all of which are different from each other, and from subjective loudness. To clearly understand these concepts, a comprehension of how we hear and how sound is propagated in free space is necessary.

Sound Pressure

The most elementary type of vibration is that which has a single frequency and is called simple harmonic motion. It is the form of vibration which characterizes a "pure" tone; for example, that given by a good tuning fork which has been struck gently. The form of this vibration and the corresponding form of the pressure variation which is propagated outwardly in the surrounding medium as a sound wave is shown in this figure.



Sine Wave

This is a sine wave; a curve having this shape can be obtained by plotting, on rectangular coordinate paper, the sine of an angle against the angle itself. Thus a tone produced by a simple harmonic sound source is often called a "pure" tone because it contains only one frequency.

The total pressure in a sound field, at a specified point and instant of time t, is given by the sum of the undisturbed atmospheric pressure Ps and the alternating pressure due to the sound wave.

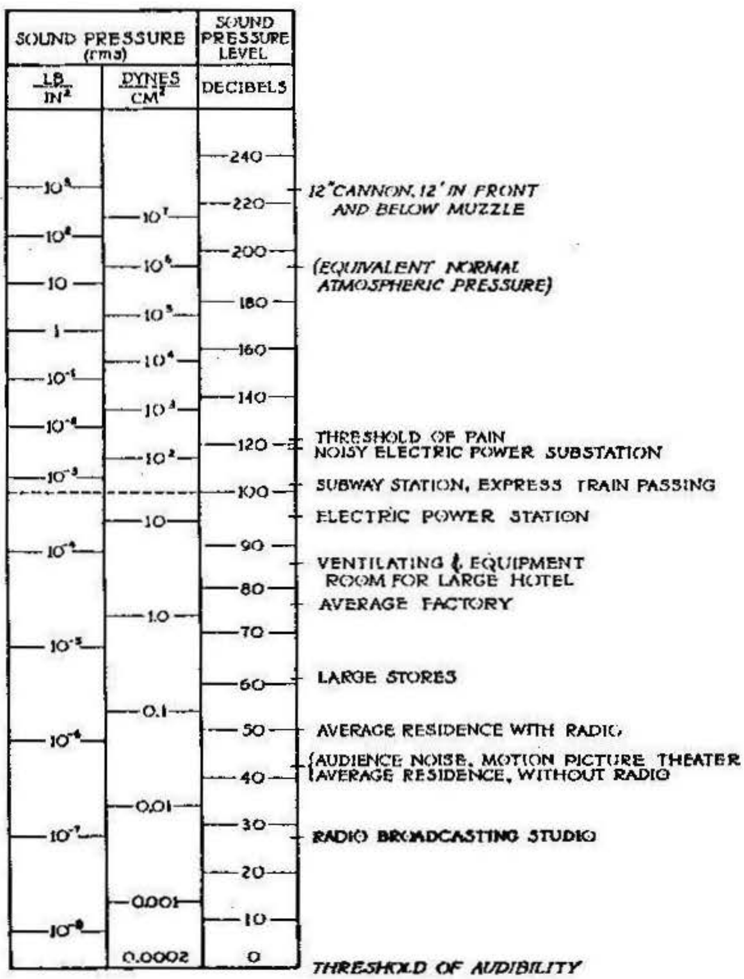
The latter is given by

$$P_a \sin (2\pi ft + \Theta$$

where:

P_a = maximum pressure amplitude
f = frequency of vibration
t = time
Θ = phase angle when $t = 0$

This particular (simple harmonic) type of wave motion is important because all sound waves can be shown to be made up of a number of different simple harmonic waves. The effective sound pressure P is the square root of the time average of the square Pa sin $(2\pi\ ft + \Theta)$. The term *sound pressure* is generally used to designate the effective value of the sound pressure. An extraordinarily small sound pressure can be detected by the ear. The following figure indicates the pressure due to noise in various locations; it shows that at the threshold of audibility the sound pressure is on 0.0000000035 pound per square inch.



Acoustical Power

The rate of emission of acoustical energy from most sources of sound, and the corresponding pressures in their resulting sound fields, are very small. For example, the average acoustical power radiated by a person speaking in an auditorium is of the order of 25 to 50 microwatts (a microwatt is one million of a watt). It would require, therefore, no fewer than 15,000,000 such speakers to generate a single horsepower of acoustical energy. With such minute amounts of sound power in unamplified speach, the resulting sound pressure in an auditorium is correspondingly small; often the average sound pressure is less than 0.1 dyne per square centimeter. In contrast with the mere 50 microwatts output of a typical speaker, the acoustical power required for good hearing conditions for speech throughout an auditorium, is 10,000 microwatts in a room having a volume of about 100,000 cubic feet.

Most musical instruments radiate a somewhat greater power than does the average human voice. The table below gives the approximate peak power for a number of typical instruments. These values are small compared to the 37-kilowatt acoustical power output of a large air-raid siren developed during world war II.

The Approximate Peak Sound Power Output of Conversation Speech and of Several Musical Instruments
(Bell Telephone Laboratories)

Source	*Peak Power in Watts*
Conversationnl Speech female	0.002
male	0.004
Clarinet	0.05
Bass Viol	0.16
Piano	0.27
Trumpet	0.31
Trombone	6.00
Bass Drum, 0.90 x 0.38	25.00
Orchestra, 75 pieces	10 to 70

Sound Intensity

The sound intensity in a specified direction at a point in a sound field is defined as the rate of flow of sound energy through a unit area at that point, the unit area being perpendicular to the specified direction. Sound intensity is usually expressed in watts per square centimeter.

As an illustration, we shall calculate the intensity 100 centimeter from the bell of a clarinet. For low-frequency tones, the clarinet approximates a point source; that is, it radiates sound nearly uniformly in all directions. (The sound waves from a perfect point source, which is far from any reflecting surface are spherical.) Let us assume that the total power output W for a sustained tone from the clarinet is 0.002 watt. Since the area

S of a sphere is 4π times the square of the radius; the area of a sphere 100 centimeters in radius is 125,600 square centimeters. Thus the power passing through each square centimeters. Thus the power passing through each square centimeter of this sphere, flowing in the outward direction — the intensity I — is

$$I = \frac{W}{S} = 0.002 \text{ watt}/125{,}600 \text{ cm}^2 = 1.59 \times 10^{-8} \text{ watt/cm}^2$$

Since the area of a sphere increases as the square of its radius, we note that the intensity of *free*[3] sound waves originating at a point source diminishes inversely as the square of the distance from the source.

The sound intensity at any distance from the source is expressed also as

$$I = \frac{P}{A}$$

Where I = the sound intensity in w/cm^2 or w/m^2
P = acoustic power in watts
A = area in cm^2 (m^2)

Since the sound radiates freely in all directions,

$$I = \frac{P}{4\pi r^2} \quad w/cm^2$$

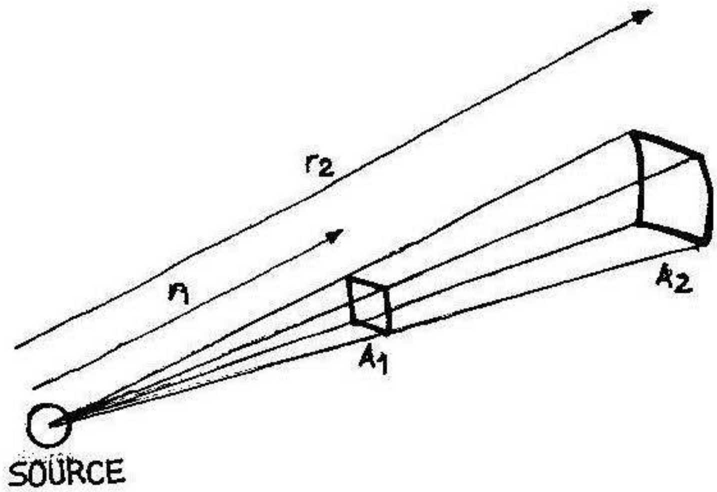
Where r is the radius of an imaginary enclosing sphere (in English units this is

$$I = \frac{P}{930 \times 4\pi^2} \quad w/ft^2$$

since there are 930 cm^2 in one sq. ft.) The intensities at distances r_1 and r_2 from the source stand in the ratio of

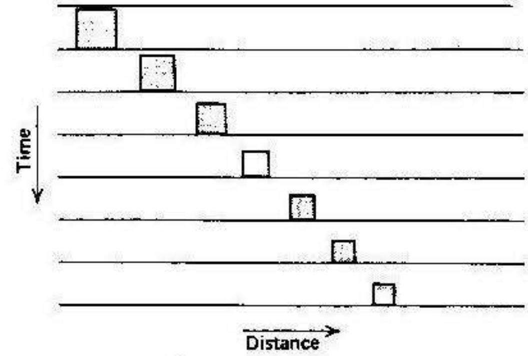
$$\frac{I_1}{I_2} = \frac{r_2^2}{r_1^2}$$

which is the formula for the classic *Inverse Square Law,* stating that intensity is inversely proportional to distance from the source.



Another figure below show graphically how a sound pulse is attenuated in strength (but not in wave form) as it travels outward from the source by action of distance.

The threshold of hearing, that is, the minimum sound power intensity that a normal ear can detect, is 10^{-16} w/cm^2 (actually the ear responds to pressure, as will be explained. The maximum sound intensity that the ear can accept without damage is approximately 10^{-3} w/cm, this gives a range of 10^{13} or 10 million million to one 10,000,000,000,000: 1).



The table below gives the reader an idea of the physical significance of these numbers. Two problems arise immediately when dealing with quantities of this type; the numbers themselves are very small and the ratios are very large. Furthermore, the human ear responds logarithmitically, not arithmetically to sound pressure (and intensity); that is doubling the intensity of a sound does not double its loudness — the change is barely perceptible.

To solve these problems it would be much more convenient if we were to construct a scale that:

a. Started at zero for the minimum sound (intensity or pressure) that we could hear.

b. Used whole numbers rather than negative powers of 10.

c. Had some fixed relationship between an arithmetic difference and a loudness change; say 10 units equals a doubling or (halving) of loudness. Thus, on such a scale, the difference between 20 and 30, and 60 and 70, would always be a doubling of loudness.

Such a scale is the decibel scale.

TABLE

Intensity (w/cm^2)		Intensity Level—	
Decimal Notation	Exponential Notation	Logarithmic Notation	Examples
0.001	10^{-3}	130 db	Painful
0.0001	10^{-4}	120 db	
0.00001	10^{-5}	110 db	75-piece orchestra
0.000001	10^{-6}	100 db	
0.0000001	10^{-7}	90 db	Shouting at 5 ft
0.000000001	10^{-9}	70 db	Speech at 3 ft
0.00000000001	10^{-11}	50 db	Average office
0.0000000000001	10^{-13}	30 db	Quiet unoccupied office
0.00000000000001	10^{-14}	20 db	Rural ambient
0.000000000000001	10^{-15}	10 db	
0.0000000000000001	10^{-16}	0 db	Threshold of hearing

Intensity Level (IL)
the Decibel (db)

The word "level" indicates a quantity relative to a base quantity. Intensity level is the ratio between a given intensity and a base intensity. If we express intensity level as

$$IL = 10 \log \frac{I}{I_o}$$

where:

- IL = intensity level in decibles
- I = intensity in watts per square centimeter
- I_o = base, that is, 10^{-16} w/cm^2 (threshold of hearing)

then we have established a scale that satisfies the three conditions set forth in the previous section. The quantity IL, intensity level, is dimensionless, since it indicates simply a ratio between two numbers. It is measured in decibles (db) for convenience in expressing the large numbers involved. The previous table above show the great convenience of using the logarithmic decibel scale as compared to either decimal notation or exponential notation. The table below gives a short listing of subjective loudness changes expressed in db. Note that 10 db indicates a doubling of loudness, as specified; 20 db is loudness doubled twice, that is, four times as loud. The difference in db between any two intensity levels, expressed as a function of these respective intensities, is

$$IL_2 - IL_1 = 10 \log \frac{I_2}{I_0} - 10 \log \frac{I_1}{I_0}$$

$$= 10 \left(\log \frac{I_2}{I_0} - \log \frac{I_1}{I_0}\right)$$

$$\Delta IL = IL_2 - IL_1 = 10 \log \frac{I_2}{I_1}$$

Example: Two sound sources produce intensity levels of 50 and 60 db, respectively, at a point. When functioning simultaneously, what is the total sound intensity level? (We assume identical frequency content and random phase; that is, the phase relationship between the two sources changes in a random manner.)

Solution:

(a)
$$IL = 10 \log \frac{I}{I_o}$$

$$\text{so } 60 = 10 \log \frac{I_1}{10^{-16}}$$

$$6.0 = \log \frac{I_1}{10^{-16}}$$

$$10^6 = \frac{I_1}{10^{-16}}$$

$$I_1 = (10^{-16})10^6 = 10^{-10} \text{ w/cm}^2$$

$$\text{and } 50 = 10 \log \frac{I_2}{10^{-16}}$$

$$5.0 = \log \frac{I_2}{10^{-16}}$$

$$10^5 = \frac{I_2}{10^{-16}}$$

$$I_2 = 10^{-11} \text{ w/cm}^2$$

(b)
$$\begin{aligned} I_1 + I_2 &= 10^{-10} + 10^{-11} \\ &= (10 \times 10^{-11}) + 10^{-11} \\ &= 11 \times 10^{-11} \text{ w/cm}^2 \end{aligned}$$

(c)
$$\begin{aligned} IL \text{ combined} &= 10 \log \frac{11 \times 10^{-11}}{10^{-16}} \\ &= 10 (\log 11 + \log 19^5) \\ &= 10 (1.04 + 5) \\ &= 10 (6.04) \\ &= 60.4 \text{ db} \end{aligned}$$

which is a fraction larger than the original 60 db of the stronger sound.

Example: Assume two noise signals of 60 db each. What is the combined strength in decibels?

Solution: One method would be to calculate levels as in the example above. A shorter method is to find the difference between the two signals and to add it to either one. Using the equation;

$$\begin{aligned} \triangle IL &= IL_{comb} - IL_1 = 10 \log \frac{I_2}{I_1} \\ &= 10 \log \frac{I \text{ comb}}{I_1} \\ &= 10 \log \frac{2I_1}{I_1} \\ &= 10 \log 2 \\ &= 10 (0.3010) \\ &= 3 \text{ db} \end{aligned}$$

This answer gives us the **extremely** important fact that doubling a signal intensity raises the intensity level by **3 db.** (In our case, the combined intensity level would be 60 db + 3 db or 63 db). **Similarly, quadrupling** a signal's intensity raises the received level by 6 db (see table below).

TABLE

Change in Level, Decibels	Subjective Change in Loudness
3	Barely perceptible
6[a]	Perceptible
7	Clearly perceptible
10	Twice or half as loud
20	Four times or one-quarter as loud

Example: Given a sound source that produces sound intensity IL at a distance d_1 from the source (the reader can substitute any numbers desired, or follow the problem with symbols), what are the intensities at twice the distance? Three times? four times?

Solution:

from the equation $\triangle IL = 10 \log \frac{I_2}{I_1}$

and equation $\frac{I_1}{I_2} = \frac{d_2^2}{d_1^2}$

or $\frac{I_1}{I_2} = \frac{(2d_1)^2}{(d_1)^2} = 4$

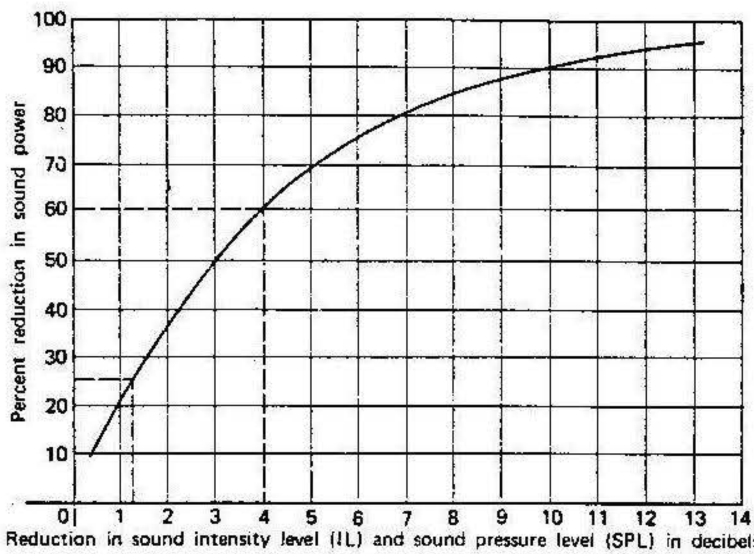
substituting in the first equation, we have

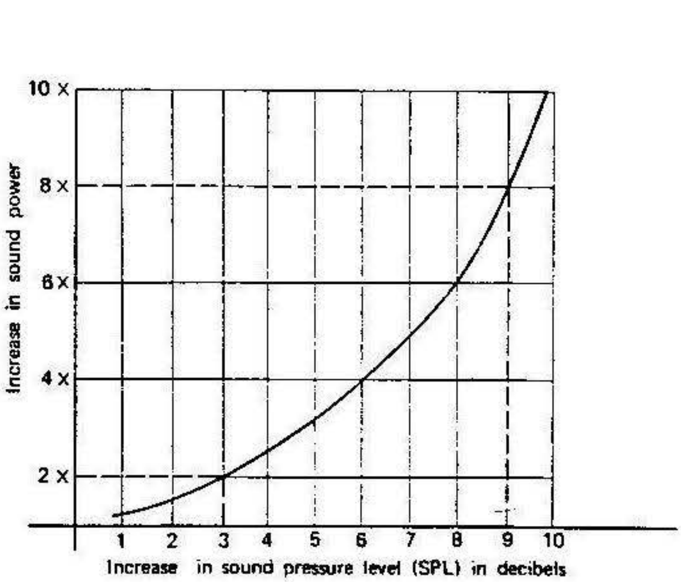
$$\begin{aligned} IL &= 10 \log \frac{I_1}{I_2} \\ &= 10 \log 1/4 \\ &= 10\,(-0.6) \\ &= -6 \text{ db} \end{aligned}$$

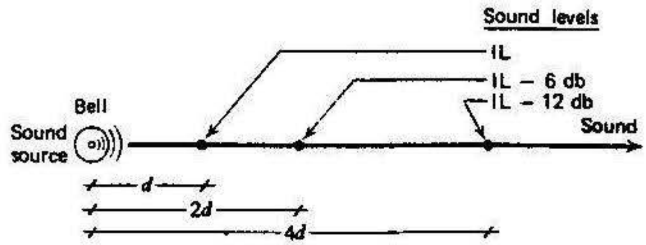
Which tells us that sound intensity level (not pressure) is reduced by 6 db. Similarly, when distance is tripled, intensity level is reduced by 9.5 db, and when distance is quadrupled, it is reduced by 12 db.

To summarize, then, intensity level increases (decreases) 3 db with every doubling (halving) of power and decreases (increases) 6 db with every doubling (halving) of distance. The following figures illustrate these relationships. The ear responds to sound pressure, not intensity. Sound pressure level (SPL) is equal numerically to intensity level (at least for normal temperature and pressure, ex.; for our use in architectural acoustics), so that the foregoing examples and manipulations of intensity level are equally applicable to sound pressure level.

The combined effect of two sounds depends upon their frequency content. In the above examples, we assumed signals either of identical frequency and random phase, or of very wide-frequency spectrum — so wide that phase phenomena are not significant. In architectural acoustics work, such an assumption is generally valid.






Sound levels
IL
IL − 6 db
IL − 12 db
Bell
Sound
source
Sound
d
2d
4d

2

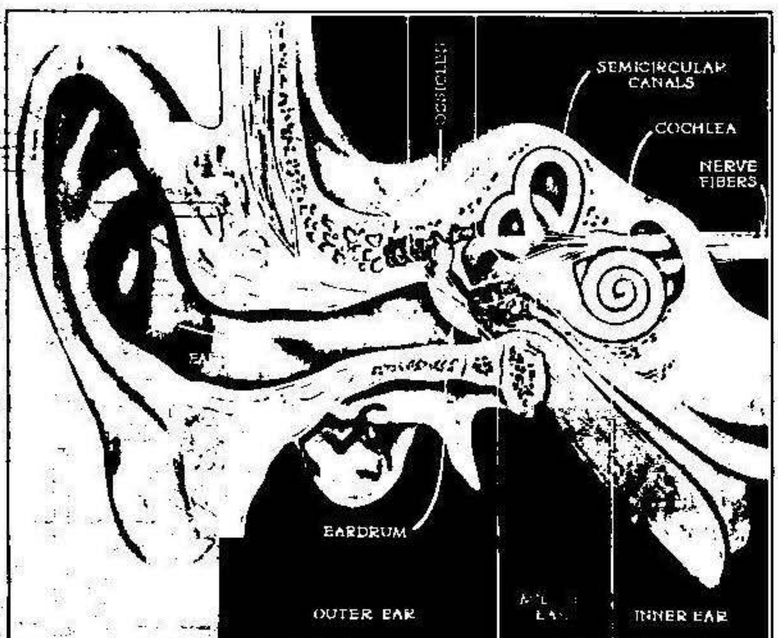
HUMAN RESPONSE TO SOUND

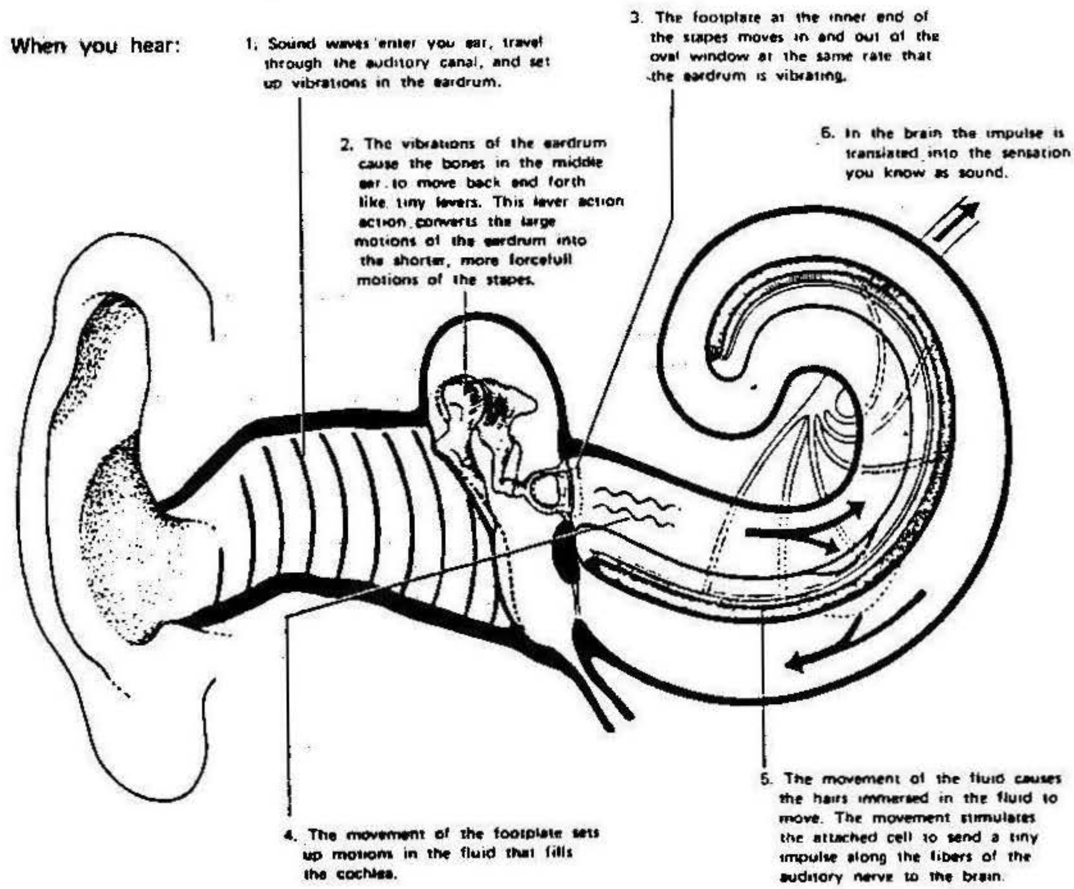
Sound Propagation Acoustic Power and Sound Pressure Level

HOW WE HEAR

The hearing mechanism, shown in cross section in the figure below can be divided into three parts: the external ear, the middle ear, and the inner ear. The *external ear* consists of an external appendage, called the pinna, and the ear canal, which is closed at the inner end by the eardrum. The outer ear is funnel shaped and serves as a sound-gathering input terminal to the auditory system,. Sound energy travels through the auditory canal (outer ear) and sets in motion the components of the middle ear.

The *middle ear* contains three tiny bones or ossides which transmit vibrations from the eardrum to the inner ear. These bones — the hammer, anvil, and stirrup — constitute a lever mechanism that communicates the vibrations of the drum to the membrane of the oval window, which is the entrance to the inner ear. The stirrup acts as a piston to transmit vibrations into the fluid of the inner ear. This fluid motion causes movement of hair cells in the cochlea, which in turn stimulates nerves at their bases, which in turn transmit electrical impulses along the eight cranial nerve, to the brain. These impulses we understand as SOUND. Thus the action of the middle ear is that of an efficient mechanical transformer coupling vibrations in the air to the liquid in the internal ear.





The inner ear has two distinct functions: (1) the maintenance of body equilibrium, accomplished by the vetibular portion of the ear, which is made up principally of three semicircular canals; and (2) the perception of sound, which is accomplished by the *cochlea* and its associated apparatus.

The cochlea is where frequency recognition is accomplished by the basilar membrane. This membrane resonates at one end at about 20 Hz and at the other at 20 KHz, giving the ear its frequency range.

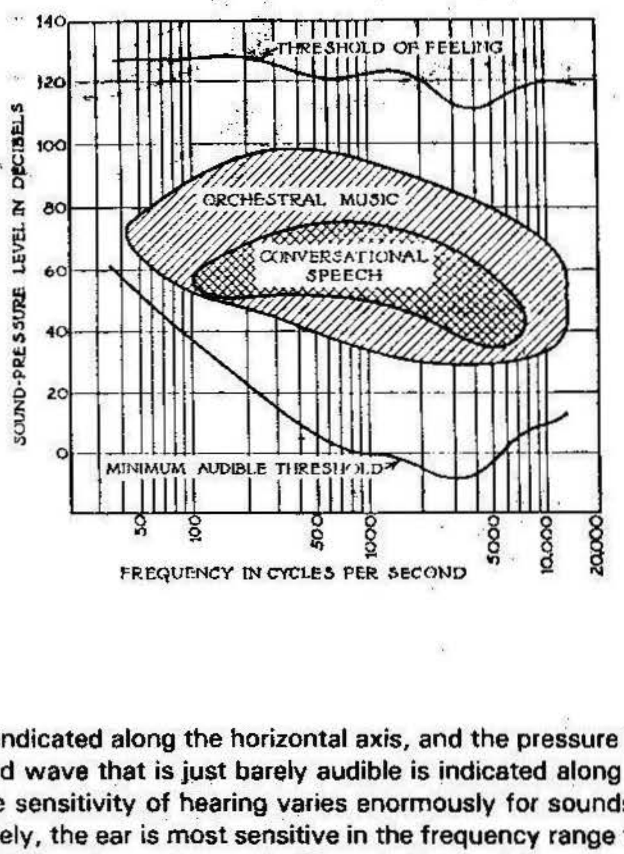
The cochlea is a liquid — filled spiral canal, subdivided along its length into two canals by a bony structure and a tough membrane. The end on one of these canals is closed by the oval window. It is through this window that the vibration of the ossicles is transmitted to the liquid in the cochlea. Sensitive nerve endings, associatted with tiny cells in a third canal, are excited by the vibratin set up in the cochlear liquid, and they send impulses to the brain by way of the nerve fibers. It is believed that the rate at which the total number of these nervous impulses are communicated to the brain determines the *loudness*. This rate depends on the number and activity (pulsing rate) of the nerve endings stimulated. It increases with the sound pressure of the wave striking the ear.

The *Pitch* of the sound sensation is determined principally by the location of the nerve endings that are most excited by the resonant vibration of various sections of the basilar membrane; however, at low pitch the frequency of arrival of the nervous impulses at the brain may be the chief determinant.

Tonal Quality is determined largely by the number, location and extent of the excited nerve endings and is complexly related to the wave form and pressure of the sound wave striking the ear.

Sensitivity of the Ear

A sound wave must have a certain minimum value of pressure in order to be heard by an observer. This value for selected observers, who have good hearing, who are facing the source of plane progressive waves and listening with both ears, is called the *minimum audible threshold* for a free field. It is shown in the lower curve of this figure.



Frequency is indicated along the horizontal axis, and the pressure level of the plane progressive sound wave that is just barely audible is indicated along the vertical axis. One notes that the sensitivity of hearing varies enormously for sounds of different frequencies. Fortunately, the ear is most sensitive in the frequency range that is most important for the intelligibility of speech sounds. Since, in the evolution of man, speech and music were developed later than the sense of hearing, it appears that speech and music have developed in such a manner as to be well adapted to the sensitivity characteristics of the ear.

An observer in the field of a free plane progressive wave will notice that, as the pressure of the wave is increased, the resulting sound becomes louder and louder until it attains a level at which the sound can be felt (a sort of tingling sensation) as well as heard. This level is called the *Threshold of Feeling.* Above this threshold, the observer experiences a mixed sensation of sound, feeling, and pain. The figure above shows that, unlike the minimum audible threshold, the threshold of feeling varies relatively little with frequency.

The ear hears and recognizes distinct frequencies, yet the hearing mechanism has the ability, apparently as directed by the brain, to either hear individual frequencies or to combine them into a single sound. Thus when we hear a string quartet we can, at will, either hear the entire quartet or each instrument individually. With concentration (vision helps in this), a "trained" ear can pick out a single instrument in an orchestra of 120 pieces, even if there is more than one such instrument in the group. Conductors do this regularly. Similarly, the ear can perform the selection known as the "cocktail party effect," that is, pick out one voice in background noise that can be 20 db louder than the wanted signal. In effect, the ear is attenuating the unwanted signals.

The minimum perceptible increment of sound-pressure level of a pure tone varies with both pressure and frequency, but, for levels greater than about 40 db above the threshold of audibility and for frequencies between 200 and 700 cycles, the minimum perceptible increment in pressure level varies from one 7000 to three quarters of a decibel. The smallest perceptible change in frequency that the ear can detect is different for different pressure levels and frequencies, but, for pure tones more than 40 db above threshold and for frequencies greater than 500 cycles, it is of the order of 0.3 percent for *monaural* listening with an earphone. In the discussion of the acoustics of rooms in later chapters, we shall see that a variation of the frequency of a sound source in a room may produce a marked variation in the pressure distribution within the room. Therefore we should expect, and rightly, that an observer could detect a smaller change in the frequency of a source in a room than in the open air.

Sound Pressure Level

At the threshold of hearing (approximately 0 db) the displacement of air molecules impinging on the eardrum, and the eardrum excursion, are approximately one Angstrom unit (10^{-8} cm), which is approximately the diameter of an atom. Were the ear an order of magnitude more sensitive, it would hear thermal noise, which is approximately at 1 micropascal (uPa). The human ear is thus close to the practical limit of sensitivity. At the other end of the pressure spectrum, the threshold of pain corresponds to 130 db, 10^8 uPa, and a molecular and eardrum motion of approximately ¼ mm. An astonishing range indeed! the pressure that corresponds to the threshold of hearing is taken to be 20 uPa or 2×10^{-4} microbars ($u$bar). As with intensity, this pressure is established as odb, for *sound pressure level* (SPL). Since the ear responds Logarithmitically to intensity and since pressure varies as the square root of intensity, we can write the expression

$$SPL = 10 \log \frac{P^2}{P_o^2}$$

or

$$SPL = 20 \log \frac{P}{P_o}$$

Where SPL = sound pressure level in decibels

P = pressure in Pascals or Bars

and

P_o = reference base pressure in pascals or bars

We have thus equalized the db scales for sound pressure level (SPL) and intensity level (IL) and the db values of the two can be used interchangeably. Obviously through, the actual intensity and the actual pressure corresponding to a particular decibel level are different - completely different, in magnitude and units.

Example: Find the sound intensity and pressure corresponding to a level of 70 db.

Solution:

(a)

$$IL = 10 \log \frac{I}{I_o}$$

where $I_o = 10^{-16}$ w/cm^2

therefore

$$70 = 10 \log \frac{I}{I_o}$$

$$7 = \log \frac{I}{I_o}$$

$$10^7 = \frac{I}{I_o}$$

$$I = 10^7 (10^{-16}) = 10^{-9} \text{ w/cm}^2$$

(b)

$$SPL = 20 \log \frac{P}{P_o}$$

$$70 = 20 \log \frac{P}{P_o}$$

$$3.5 = \log \frac{P}{P_o}$$

$$10^{3.5} = \frac{P}{P_o}$$

Since $P_o = 2 \times 10^{-4}$ μbar

$$P = (2 \times 10^{-4})(10^{3.5})$$

$$= 2 \times 10^{-0.5}$$

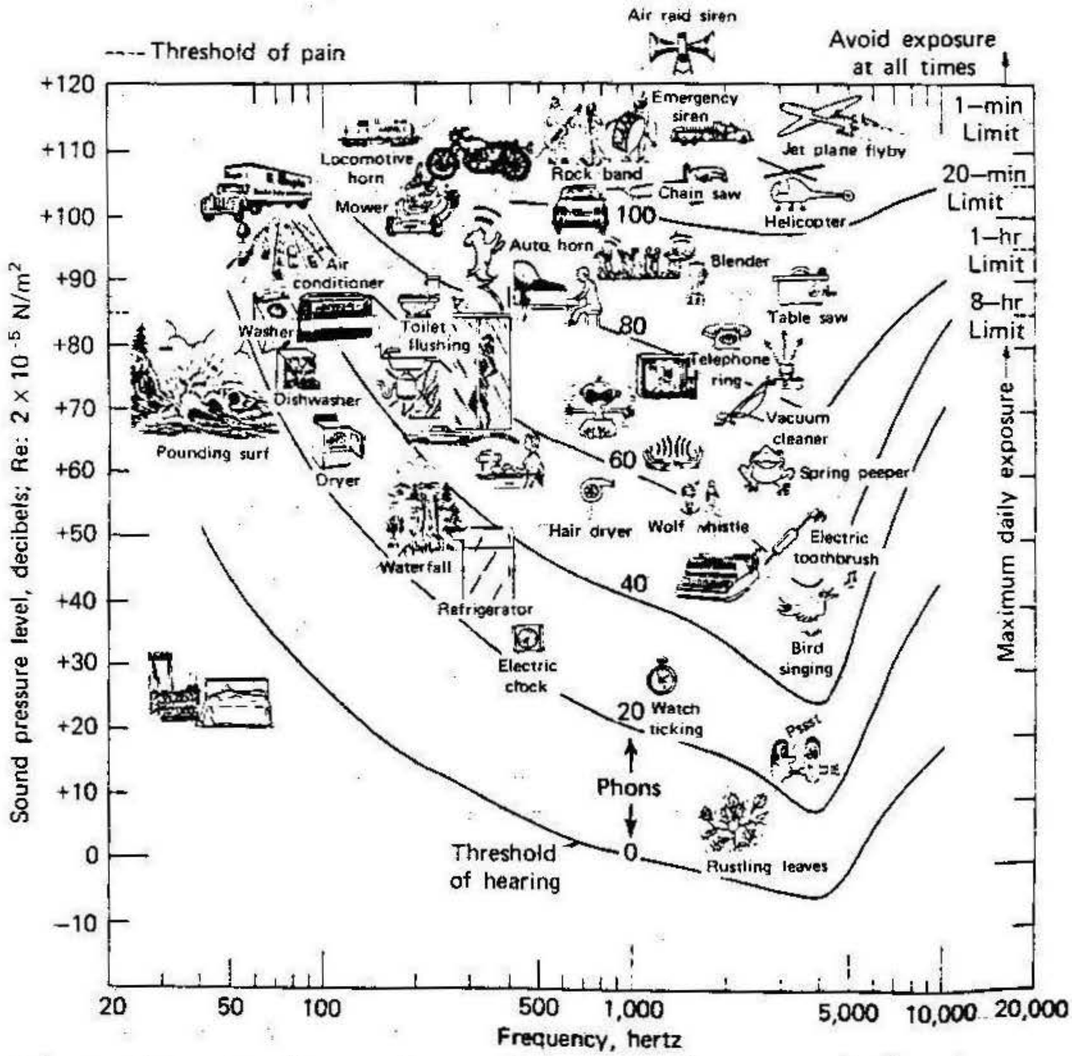
$$= \frac{2}{\sqrt{10}} = 0.63 \ \mu\text{bar}$$

$$= 0.063 \text{ Pa}$$

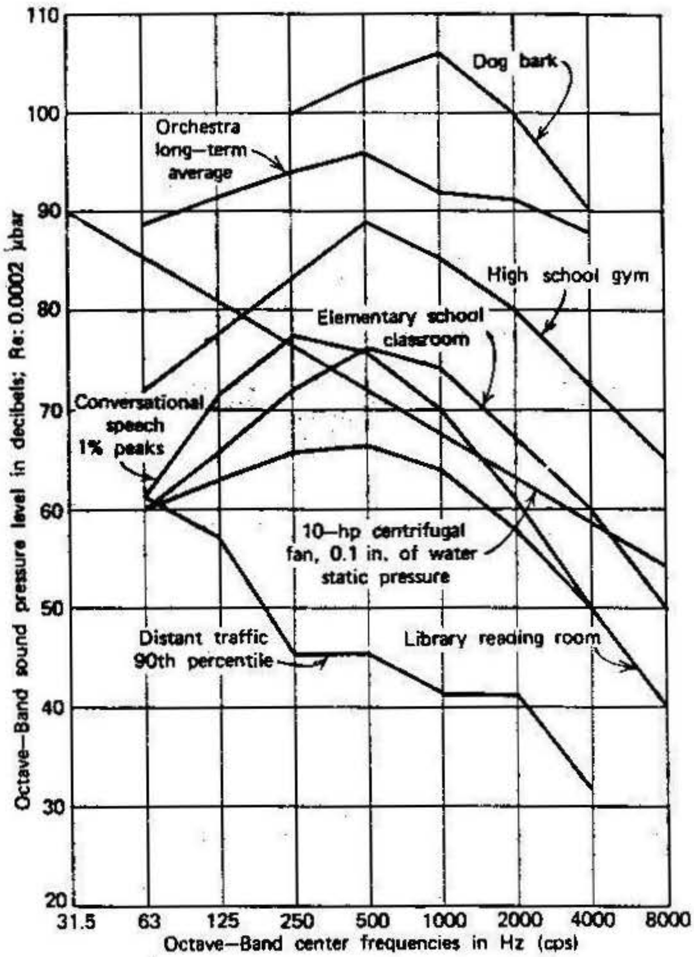
Assigning a single-number decibel level to a sound presents two difficulties:

1. The sound pressure level varies with time.
2. The different components of the sound vary in pressure level.

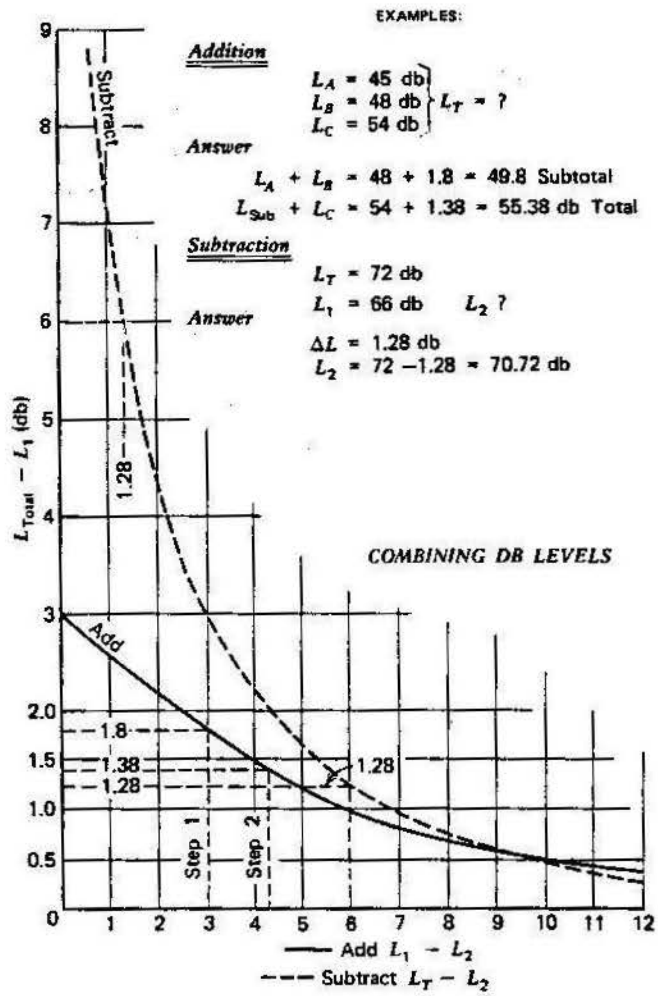
Indeed, this is the situation that normally exists, since single-frequency, constant level sounds are unusual. To overcome this problem two techniques are used. If a sound has a dominant frequency, that frequency's level can be used.



This would be the case for a relatively constant sound such as a motor, or a fan or blower. Other sounds that vary widely in level and frequency can be plotted on an octave band chart with maximum level for a minimum percent of time see figure next page.

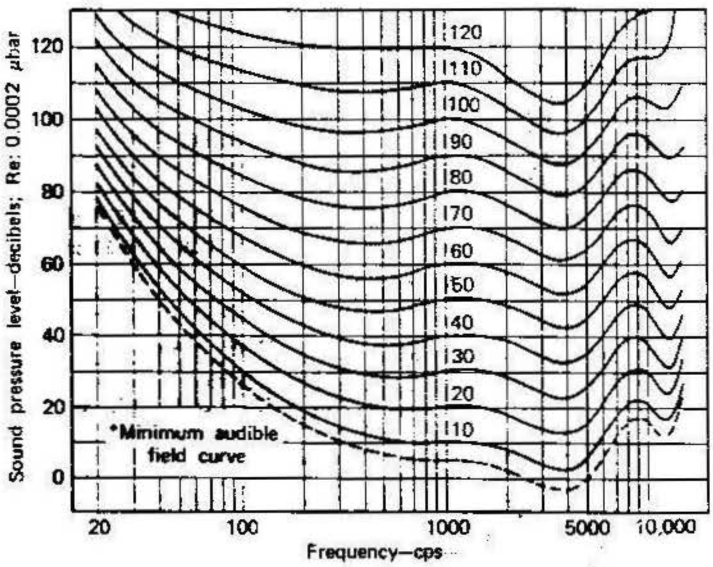


Thus vehicular traffic is shown by the level exceeded only 10% of the time. Speech sounds are those that will be exceeded only 1% of the time. The single-number levels in the table below have been assigned on this basis, and are primarily useful to establish a mental-aural comparison base and to use in maximum exposure calculations, as are discussed in the next few pages under High noise levels; Where the position of the listener is not specified in the table, it is assumed to be at normal close distances, that is, 10 to 20 ft (3.00m to 6.00m) from a train, 3 to 5 ft (0.90 to 1.50m) from a radio and the like. The somewhat tedious calculations involved in combining decibel levels of either sound pressure level or intensity level are eliminated by using the curves of the figure below, keeping in mind that this technique is only completely accurate for uncorrelated sound sources.



Loudness Level — The Phon Scale

The loudness of a sound (that is, the magnitude of its sensation) depends not only on the pressure of the sound but also on its frequency spectrum. Loudness can be described quantitatively in terms of another subjective characteristic of sound, the so-called loudness level, which itself is defined in terms of the sound pressure and frequency of a pure tone; see figure next page.



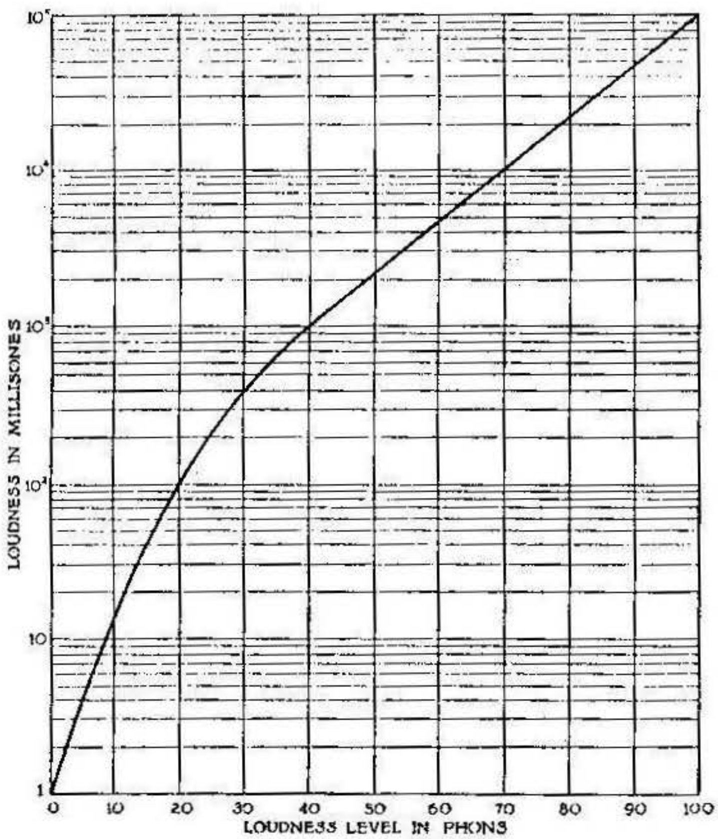
These curves are the well-known Fletcher-Munson contours of equal loudness. They were obtained by employing a pure 1000-cycle tone as a reference tone and adjusting the sound-pressure level of tones of other frequencies until they were judged to be of the same loudness as that of certain arbitrarily chosen pressure levels of the reference tone. Thus, by definition, the *loudness level,* in *Phons,* of a sound is numerically equal to the sound-pressure level, in decibels, of the 1000-cycle reference tone which is judged by listeners to be equal in loudness. For example the figure above shows that 500-cycle tone having a sound level of only 25 db sounds equally as loud as a 50-cycle tone having a sound level of 64 db. Both have a loudness level of 20 phons. Notice that at low frequencies a given change in sound level produces a much larger change in apparent loudness than does the same change in sound level at higher frequencies.

The human ear is not uniformly sensitive over its entire frequency range of 20 Hz to 20 KHz. At the upper limit the 120 to 130 – db pain threshold occurs at all frequencies. However, at the lower limit, the 0-db threshold only occurs at 1000 Hz, at which frequencies the threshold is about – 5 db. This nonlinear response exists throughout the ear's entire range. To determine the nature of this nonlinearity a great number of tests were conducted with pure tones at different frequencies, in which the listener was asked to equate loudness of signals. These tests resulted in a family of curves called *equal loudness level contours* or, alternatively, Fletcher Munson equal loudness contours (after two of the principal researchers). These curves as shown in the above figure, are internationally recognized and standardized, and are used as the reference for normal hearing response. They are also used to "weight" measuring devices as is explained in the next page, measurement of sound pressure level (SPL). Note that by definition.

1. All points in a single contour have the same subjective sensation of loudness.
2. The loudness level in *phons* is defined as the db level of that contour at 1000Hz.

The Sone Scale

The loudness of a sound is related to the total nerve energy produced by the sound in the ear, whence it is sent to the brain. It is measured in *sones*, millisones, or loudness units (1 sone =1000 millisones =1000 loudness units). A loudness of 1 millisone corresponds to the threshold of hearing, a loudness of 10 sones is twice as loud as a loudness of 5 sones and 10 times as loud as 1 sone, etc. The relationship between loudness and loudness level is given in this figure.



This curve applies to sounds of any frequency, or any combination of frequencies. For example, if the loudness level of a sound is 40 phons, it will have a loudness of 1000 millisones or 1 sone; if the loudness level of a sound is 70 phons, it will have a loudness of 10 sones. In the range above 40 phons (the range of chief interest in architectural acoustics), a change in loudness level of 30 phons corresponds to a tenfold change in loudness, and a change in loudness level of 9 phons corresponds to a twofold change in loudness. This relationship is of considerable interest in regard to the reduction of noise in rooms by sound absorption or by sound insulation. Thus, a reduction of loudness level in a room from 60 to 51 phons will be judged by the average listener as a reduction in loudness of one half.

Since the phon scale is based on decibel levels at 1000 Hz, it too is a logarithmic scale in which a *doubling* of loudness corresponds to an *increase* of 10 phons. The sone scale was developed because most people much prefer an arithmetic scale, that is, one where doubling loudness, would result in doubling the loudness index. The relation between the logarithmic scale phon and the arithmetic scale sone is

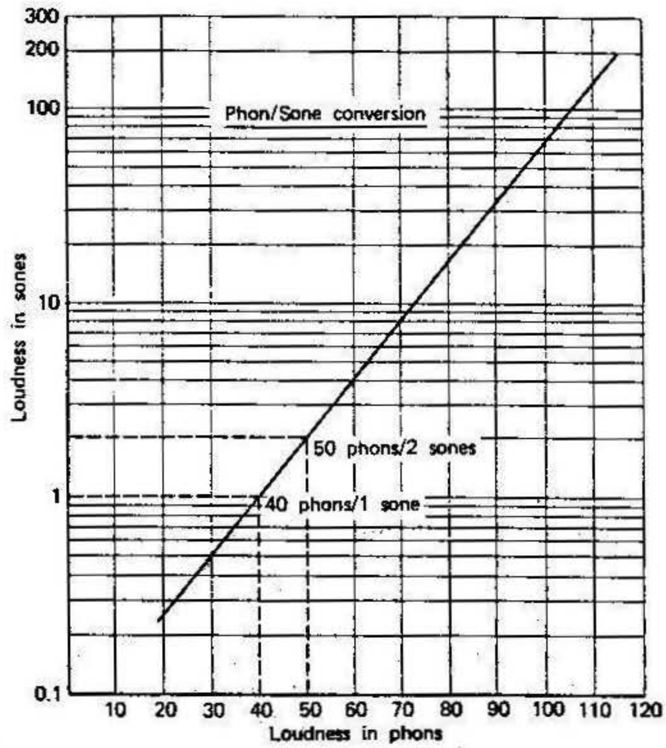
$$S = 2\left(\frac{P-40}{10}\right)$$

or

$$\log S = 0.3\,P - 1.2$$

where : S = loudness in sones
P = loudness in phons

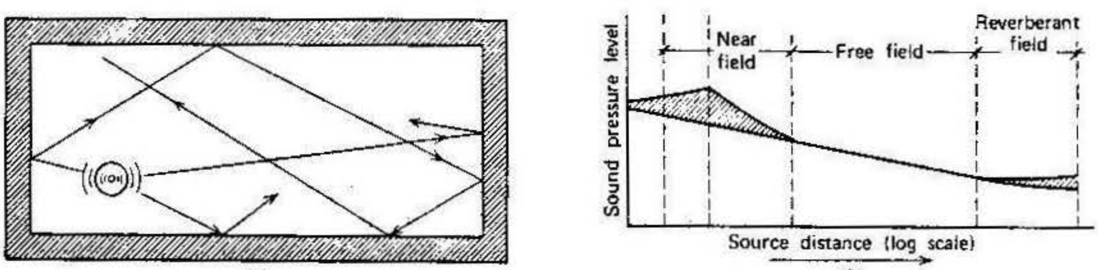
A nomograph and curve are given in the following figure for conversion between the two quantities. Although both are in use, single-number decibel A ratings are most frequently found in the literature.



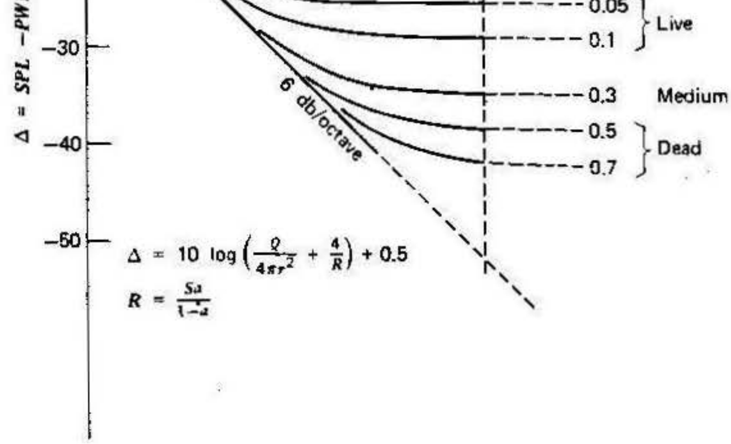
Phons	10	20	30	40	50	60	70	80	90	100	110	120
Sones	0.125	0.25	0.5	1.0	2	4	8	16	32	64	128	256

Sound Fields in an Enclosed Space

When a sound propagated in an enclosed space reaches a wall or other large (with respect to wavelength) obstruction, part is reflected and part absorbed. The sound at any point in the room is then the combination of direct sound from walls and other obstructions. If the reflections are so large that the sound level becomes uniform throughout the room, the field within the room is termed a *diffuse* one (no shadows), and intensity measurements with respect to a specific source are meaningless. Of course, it is our intention to measure sound pressure level at a specific point, such as a seat in an auditorium, then the type of field in the room is irrelevant. Most rooms do not have such a high level of reflection that a diffuse field is created. Instead, there is a near field near the source, a *free field* at a distance, and a reverberant field near the walls.



(a) *(b)*



They can be recognized as follows.

1. The near field is generally within one wavelength of the lowest frequency of sound produced by the source. Within this distance sound-pressure-level measurements vary widely and are not meaningful. (The maximum wavelength for the human male voice is about 3.30 m or 11 ft.)

2. Near large obstructions such as walls, the *reverberant field* is dominant and approaches a diffuse condition. In auditoriums the reverberant (diffuse) field predominates and sound pressure level remains relatively constant beyond the free field area.

3. The *free field* exists between the near and reverberant fields, and there intensity varies as pressure squared and inversely with distance. In this field, sound pressure level drops 6 db with each doubling of distance from the source, and it is in this field that meaningful sound-pressure-level measurements can be made.

Many enclosed spaces are so small or so reverberant that no free field exists. In such instances it is possible to measure acoustic power output from which intensity levels can be calculated. Indeed, because accurate measurement of sound pressure level due to a single source is difficult, manufacturers very frequently supply sound power and/or sound power-level data for their equipment. These figures are derived by suspending the equipment in a reverberant chamber so as to establish a spherical wave in a diffuse field.

Then $$W = \frac{13.8 p^2 v}{c^2 T_r}$$

Where

W = total sound power in watts
v = volume of the reverberant chamber
c = 344 m/sec. sound velocity in air
T_r = reverberative time in seconds (measured)
P = sound pressure in Pascal (Newtons/m^2)

Quantity p is calculated from measured sound pressure level.

Since $SPL = 20 \text{ Log } \frac{P}{P_o}$

and Since Po is base pressure of 2×10^{-5}Pa,

$SPL = (20 \log p + 94)$db

Sound pressure level (SPL) as the resultant "noise" or sound in an enclosed space, resulting from a source in that space, and affected by the characteristics of the space and the position of the listener. It is thus an end effect. The *sound power level* (PWL) is a measure of the amount of sound generated by a source, independent of its environment. In free space the two quantities are simply related by the inverse square law SPL = PWL −20 log 4 + (Q −1)db whereas in enclosed spaces the room characteristics come into play.

Roughly speaking, an analogy to lighting can be drawn: SPL corresponds to room illumination, that is, footcandles, and PWL corresponds to the lumen output of the source.

Reverberation Time is defined as the time necessary for the sound to drop 60 db, that is, to effectively become inaudible, after power is shut off. (Reverberation time can also be calculated in terms of a room's dimensions and absorption coefficient, as will be discussed in the next pages on Reverberation.

Once W, the sound source's power level is determined, it in twin can be used to calculate the sound power level, PWL, in decibels:

$$PWL = 10 \log \frac{W}{W_o} \text{ db}$$

Where

PWL = sound power level in decibels
W = sound power of source, in watts
W_o = base power, 10^{-12} W

In general, manufacturers will furnish W and PWL for equipment. It is only necessary to calculate these parameters when measurements are taken on a source of unknown power output and level. Given PWL (either listed or calculated) the sound power level it would generate in an enclosed space can be calculated as:

(a) for a sound souurce witt no directivity, in a large space,

$$SPL = PWL + 10 \log \left(\frac{1}{12.5r^2} + \frac{4}{R} \right) + 0.5$$

Where SPL = sound level in db
PWL = sound level in db
r = distance from source in feet
R = room constant in square feet

the factor R can be calculated from

$$R = \frac{S\bar{a}}{1-\bar{a}}$$

Where

R = room constant in square feet

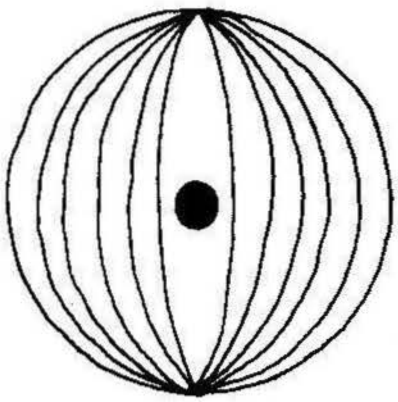
S = total room surface area in square feet

$\overline{a}$ = average absorption coefficient of all materials, in sabins (as discussed in the later sections on Barrier Mass, Building noise control)

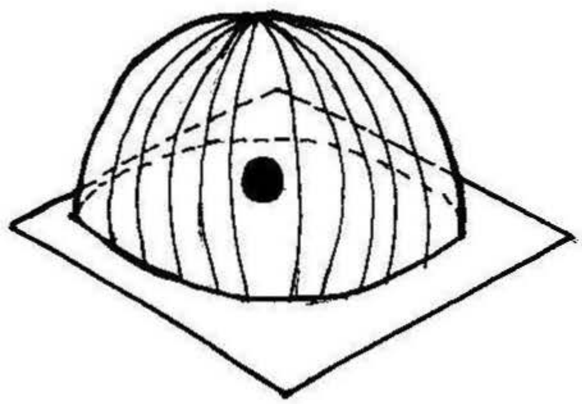
(b) For a sound source with directional characteristics, the applicable equation is

$$SPL = PWL + 10 \log \left(\frac{Q}{12.5r^2} + \frac{4}{R} \right) + 0.5 \text{ db}$$

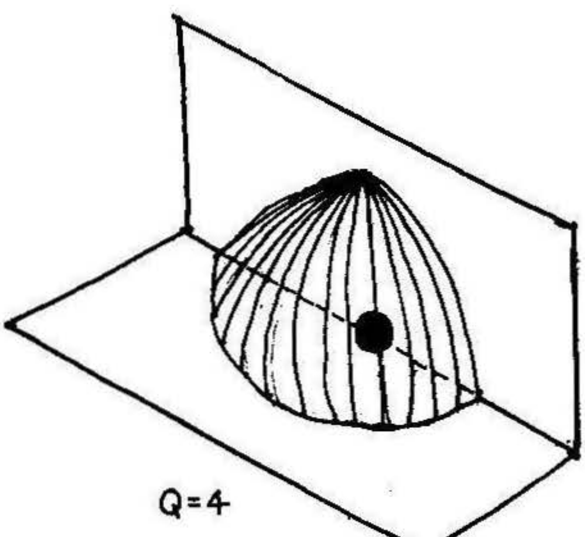
Where Q is a directivity factor and all other factors are as in equation (a) above. The directional constant is either inherent in the sound source, and as such will be part of the given data, or can be obtained from the figure below for a nondirectional source made directional by adjacent, reflecting surfaces.



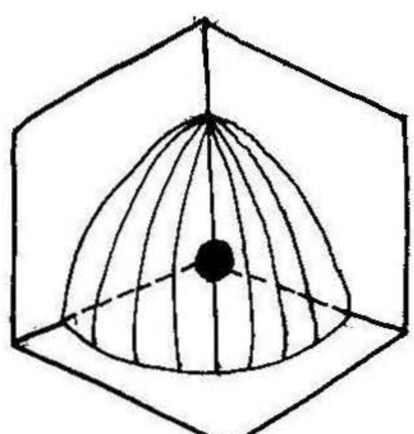
Q = 1



Q = 2



Q = 4



Q = 8

Sound Power and Pressure Levels In Free Space (outdoors)

Although the propagation of sound outdoors may not appear to be of immediate importance in architectural acoustics, outdoor noise sources such as traffic, cooling tower, and aircraft are frequently loud enough to disturb activities within or immediately adjacent to a building. Conversely, the noise made by building equipment, such as cooling towers, heat pumps, and even window air conditioners may be sufficiently loud to disturb neighbors in a nearby building. For this reason, it is desirable to have some basic understanding of outdoor sound propagation.

For preliminary evaluation of an outdoor noise problem, assuming a nondirectional source, one needs to know only the power level radiated by the source as a function of frequency and time; from this one can establish the intensity level of sound at the appropriate distance as follows:

$$SPL = PWL - 20 \log r + (Q-1) \text{ db}$$

Where

SPL = sound pressure level
PWL = equipment power level
r = distance from the source, in feet
Q = directivity factor
(see figure, Diagrams above)

This formula is fairly accurate for a small source. For large sources such as cooling towers and traffic, which do not exhibit inverse square properties, sound level estimates are best made, on the basis of experience and empirical data beyond the scope of this book. For small outdoor sources, the equipment power level can be estimated by measuring the sound power level at 5 ft and adding 15 db. Other factors, such as moisture in the air, the presence of trees, wind, and temperature gradients, will affect outdoor sound propagation to some extent but they can be ignored except when great distances (ex: over 1000 ft.) are involved. Barrier walls (such as solid fences) are an influence only when the wall is high, wide, and near the source, or near the listener. The reader is cautioned to be chary of simple solutions to barrier attenuation problems. Noise travels through, around, and over barriers. Simple graphical solutions most often assume point sources and infinitely long barriers; situations that are not even approximated by actual field situations, and that yield misleadingly high attenuation figures, particularly at low frequencies.

Others Factors in Hearing

(a) Masking

When two separate sources of sound are perceived simultaneously, the perception of each is made more difficult by the presence of the other. This is known as masking, which is defined as the number of decibels a sound has to be raised above its threshold when perceived alone, to be perceived in the presence of another sound. Effectively then, masking is greatest when two sounds are close in frequency or frequency content, since the ear has greater difficulty separating them. Also, a low frequency will more effectively mask a high frequency than the reverse, for the same decibel levels. With broad-frequency sounds the masking effect is difficult to predict, Since it depends in part on how "hard" the listener is listening. Masking is an extremely important technique in noise control where background noise levels are deliberately manipulate to mask unwanted sounds. The background noises used for this purpose are of the broadband continuous variety, which are themselves noinformation bearing. They serve to obliterate lower-level, information-bearing sounds that would cause annoyance.

(b) Time

As stated above, impulse sounds are apprehended at lower levels than the same sound intensity over a longer period. Similarly, because of the time-constant of the ear's mechanical linkages, sounds closer than 10 msec apart cannot be distinguished from each other, and those up to 50 msec apart are poorly distinguished (see criteria for speech rooms in the next pages). Beyond this point differentiation becomes increasingly clear. This effect is of particular importance in the design of halls and auditoriums, with respect to reception of echoes.

(c) Directivity

The exact mechanism by which the binaural aspect of hearing detects direction is not clearly understood. The single ear is not phase sensitive, but it may be that binaurally, phase sentivity exists, at least at low frequecies, and that this assists in detection of direction. At high frequencies, phase detection is clearly nonexistent and sense of direction may be due to diffraction effects around the head. These effects would also explain the accuracy of detection in a horizontal plane, which research indicates to be in the order of 5 °change. It would not explain how the ears detect changes in the vertical plane immediately in front of the listener. This latter situation, although much less; accurate than horizontal plane detection, definitely exists. In enclosed space, reverberation will blur most phase differences and "stereo" information will be almost completely dependent upon high frequencies in the near field.

(d) Concept of Reverberation

Although this is not strictly a hearing phenomenon it is one of the most pronounced hearing reactions in an enclosed space. Simply, it is the ear's reaction to echoes in an enclosed spaced, giving an impression of "liveness" or "deadness". We can obtain a good approximation of the subjective feeling of liveness of a room, for purposes of speech, from the relation

$$T = 0.3 \log \frac{V}{10}$$

Where T = optimum reverberation time in seconds, for speech

V = room volume in cubic meters

for instance, a typical classroom might have a volume of 150 m^3 (5300 cu ft.). Optimum reverberation time is

$$T = 0.3 \log 15$$
$$= 0.35 \text{ sec.}$$

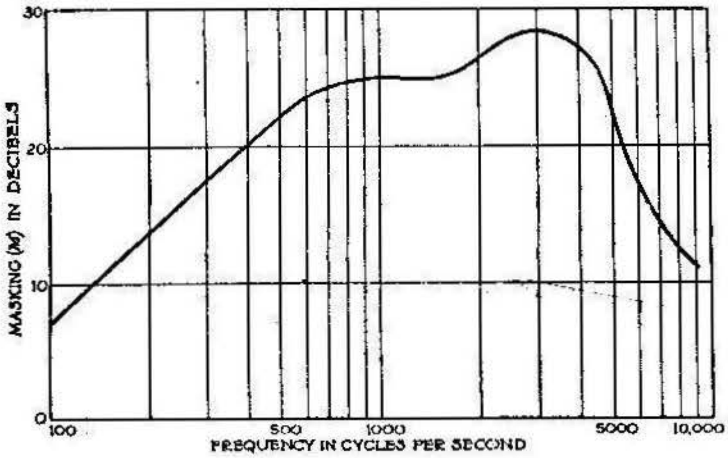
Reverberation times longer than this would sound live; shorter ones dead and flat. Indeed an increase of 20% in reverberation time would make the room excessively live and boomy and would negatively affect speech intelligibility. (see next chapter under reverberation and criteria for speech rooms).

Effect of Noise on Hearing

Many auditoriums and theaters are not adequately insulated against noise. Everyone has probably had the experience of being unable to hear some critical lines in a play because noise from the foyer or street often occur just as these lines are spoken. Inspite of the apparent correlation, no one has demonstrated the existence of a "masking demon" that knows the play and takes delight in making noise at these most crucial moments. However, one may legitimately conclude that, aside from the annoyance that it causes, noise has the effect of reducing the acuity of hearing; that is, it elevates the threshold of audibility. This shift in threshold of acuity is called *masking,* as explained earlier, and the shift, in decibels, defines the amount of masking. Unless the loudness of speech or music cannot be fully recognized or appriciated because of the masking effect of the noise; it is impossible to ignore completely a loud noise and listen only to the wanted sound.

The subject of the interfering effect of noise is so pertinent to the hearing of speech and music in auditoriums that considerable space will be devoted to it in subsequent chapters. Only a few of the fundamental properties of auditory masking are presented in this section.

Masking data are generally represented in the form of a curve called a *masking spectrum* (sometimes called a masking audiogram) which gives the number of decibels at each frequency that the threshold level of a pure tone is shifted when heard by a normal observer in the presence of masking sounds. As an illustration, the masking spectrum due to "average room noise" is given in this figure.



For instance, a tone of 1000 cycles would have to be raised 25 db above the *minimum audible threshold* to be heard in the presence of this average room noise. The masking spectrum in this case, and in general, is not constant with frequency. It depends on the pressure level and the nature of the masking sounds. Here we shall discuss two types of masking sounds: first, a sustained pure tone; and second, a continuous noise spectrum typical of those which occur in auditoriums.

Experiments indicates that low-pitched tones, especially if they are considerable loudness, produce a masking effect upon high-pitched tones, whereas high-pitched tones produce only little masking upon low-pitched tones. The auditory masking of one tone upon another is greatest when the masking tone is almost identical with the masked tone. In general, all tones, especially if they are loud, offer considerable masking for all tones of higher frequency than the Masking tone; Therefore, very intense low-frequency hums or noise are especially troublesome sources of interference for the hearing of speech or music since they mask nearly the entire audible range of frequencies.

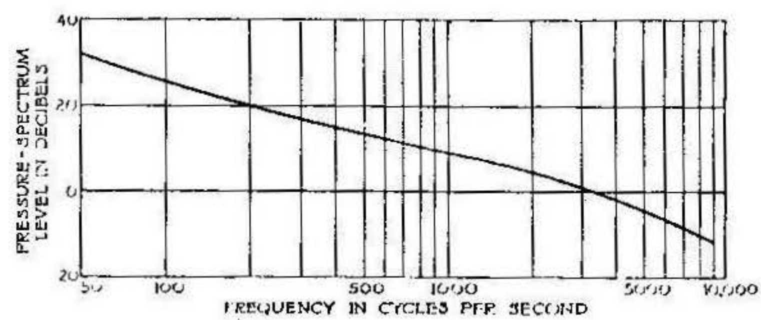
Calculation of Masking Spectra from Sound-pressure Spectra

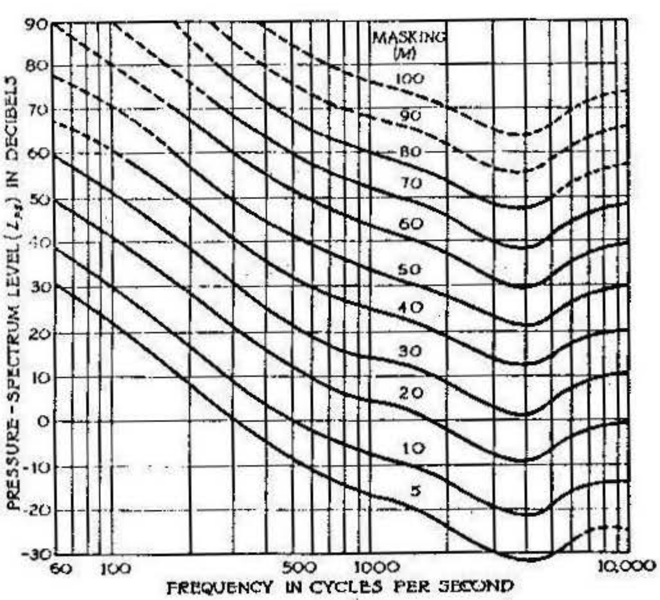
The level of the noise surroundings the listener – not his threshold of audibility – generally determines the lowest value of sound pressure he can hear; that is, the noise elevates his apparent threshold audibility. The effect of this increase in the threshold of audibility is the reduction of intelligibility of speech for him, especially when the speech is at low levels. It is important, therefore, that we should be able to predict, at least approximately, the masking effect in the average room or auditorium.

The masking of noise depends not only on its total sound pressure, but also on its frequency or *spectral* distribution. This distribution can be obtained by the use of a *sound analyzer,* a device which measures the sound pressure within a limited frequency range called a *band.* By "sweeping" this band across the entire audible range it is possible to determine how the sound pressure is distributed with respect to frequency. Not all analyzers have the same band width; in order to make sound frequency analysis comparable sound pressures P_w for a band having a frequency width of *w* cycles are frequently converted to pressure-spectrum levels L_{ps} (that is, the pressure level for a band 1 cycle wide) by the equation.

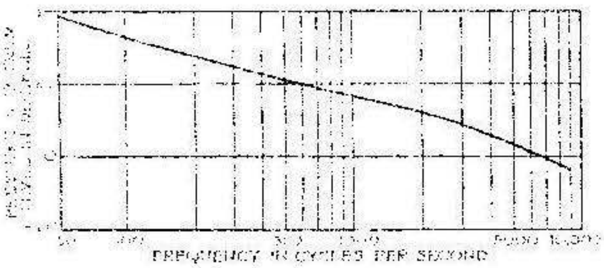
$$L_{ps} = 10 \log_{10} \left(\frac{P_w / 0.0002}{w} \right)^2 \text{db}$$

A graph of pressure-spectrum level vs frequency is called *sound spectrum* or a *noise spectrum.* The spectrum for average noise is shown in the figure.

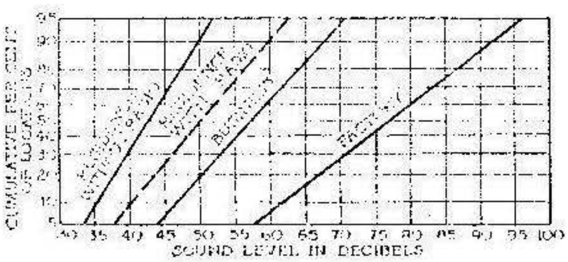




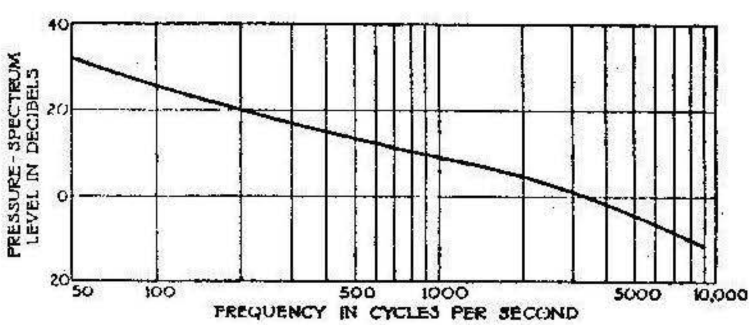
The first step in computing the masking effect of noise is to determine the spectrum level of the noise, using the above equation. Having obtained the sound spectrum of the noise, the masking M at every frequency is determined from this figure.



As an illustration we shall calculate the masking spectrum due "to typical room noise". Surveys of room noise in telephone suboribers locations have been by the bell telephone laboratories.



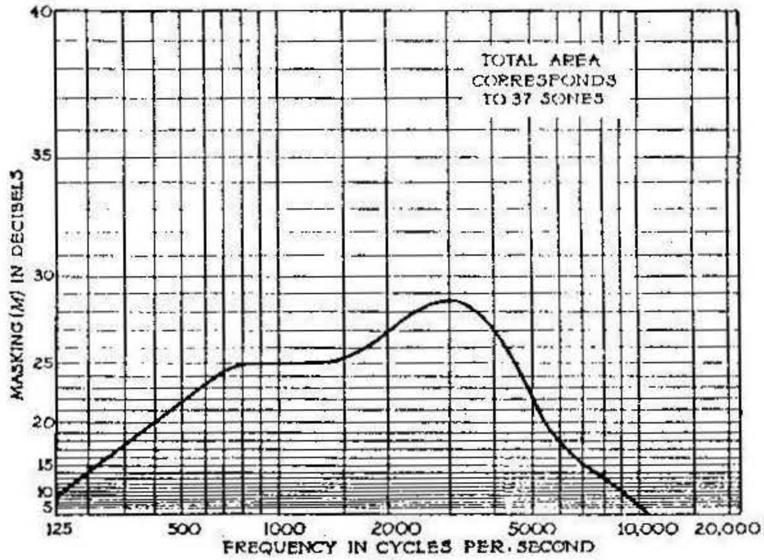
The average sound-pressure level in residences with radios turned off, as measured with a sound-level meter (using the 40 — db frequency weighting network) was found to be 43 db. About half of the residences had sound levels between 38 and 47 db, and 90 percent had levels between 33 and 52 db. The noise spectra for all types of rooms are similar, and they have the shape shown in this figure.



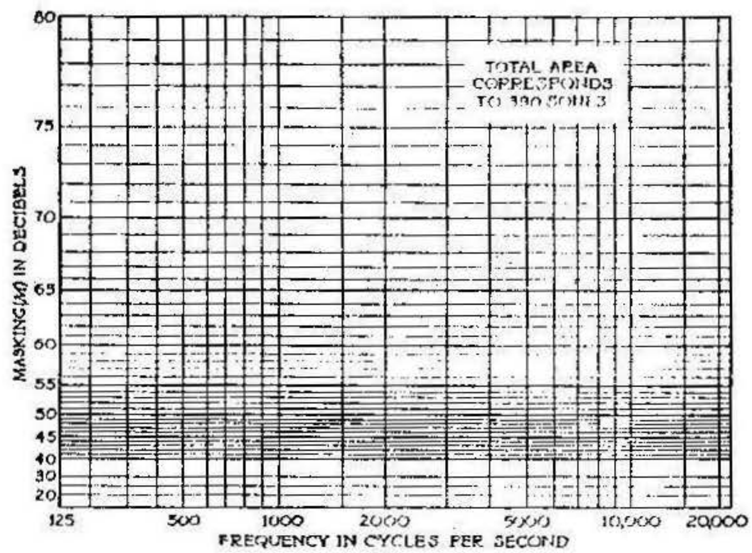
Closely to what is recognized by the ear, physiological units, such as loudness of a sound whose spectra does not change abruptly in magnitude from one frequency region to another, such as average room noise.

(1) Determine the *masking spectrum* from the *sound pressure spectrum* by the method given above.

(2) Plot the masking M on the special loudness computing chart on figure (a) or (b) below.



(a)



(b)

We have chosen the ordinates of this curve so that the total sound level, (that is, the level of the integrated value of L_{ps}) corresponds to 43db, the average sound level in residences. The masking spectrum (shown in the first figure on *Masking* spectrum due to "average room noise") for this noise distribution is then obtained from the other figures shown earlier (fig. on masking vs frequency).

For example, in the first figure, at 200 cycles, the pressure spectrum level is 20 db. Then in the figure page no. 43, the value of M for L_{ps} equal to 20 db at 200 cycles is 13 db. Other points for deriving the curve in the first figure were obtained similarly. The application of these data is limited to portions of the noise spectrum that do not exhibit abrupt changes with frequency.

Loudness Calculations for a case of Typical Room Noise

The reduction of room noise is a routine task in architectural acoustics. It is most advisable to stop the noise at its source, but frequently this procedure is impossible or impractical. Then the room noise is usually decreased by the installation of sound-absorptive material. The over-all reduction in the level of the noise can be given in decibels, but in order to express the decrease in terms which correspond more.

(3) Determine the area under this curve; the area is directly proportional to the loudness, the constant of proportionally depending on the unit of area used. The total area of the loudness computing chart in figure (a) above corresponds to 37 sones. Thus, if the area under a curve plotted on this chart is 10 percent of the total area of the chart, it represents a loudness of 3.7 sones. The total area of the chart in figure (b) corresponds to 390 sones; This chart should be used when the other one is not large enough to accomodate the masking spectrum.

As an illustration we shall calculate the loudness of the average room noise spectrum shown in the figure (average room noise spectrum) previous pages. Its masking spectrum was determined and plotted in the other figure on (masking spectrum due to "average room noise"). Replotting this data on the figure (a) above, we find that the area under this curve is 21% of the total area of the loudness computing chart. Hence, the loudness due to typical room noise in 21% of 37 sones, or 7.8 sones. A method is given in the later chapter on (Reduction of Air-Borne noise) for the calculation of the loudness reduction of room noise resulting from the installation of sound-absorptive material.

3

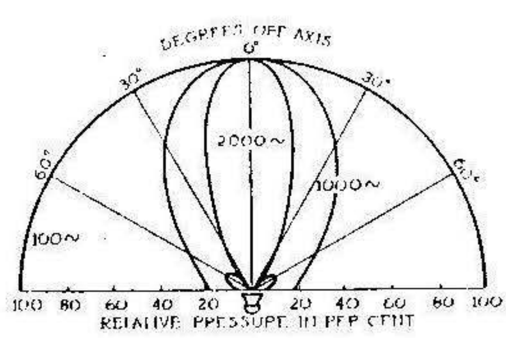
SOUND SOURCES

DIRECTIONALITY OF SOUND SOURCES

One of the important characteristics of a sound source is its *directionality,* that is, the way in which it distributes sound in a region free from reflecting surfaces. For good listening conditions, this characteristic must receive special consideration in the placement of loudspeakers in all sound-amplication systems. Although the radiation patterns of different sound sources vary considerably, most sources have the following properties:

(1) When the wavelength of the emitted sound is very large in relation to the dimensions of the source, energy is radiated uniformly in all directions.

(2) On the other hand, when the wavelength is small in relation to the dimensions of the source, most of the radiated sound is confined to a relatively narrow beam, the higher the frequency, the sharper the beam. As a result, all the listeners in an auditoruim may receive almost the same amount of power for the low frequencies emitted by the loudspeakers of the sound-amplication system. However, those away from the axes of the loudspeakers may not receive an adequate amount of sound at the higher frequencies.

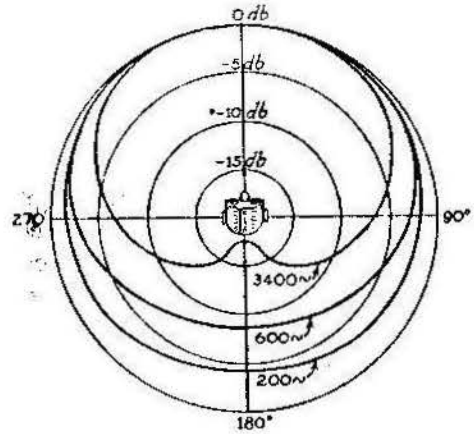


The distribution of sound pressure emitted by an ordinary loudespeakers 12 inches (0.30 M), mounted in a very large baffle, is shown in the figure.

In this figure, the distance from the origin of any point on a curve is a measure of the relative sound pressure in the direction corresponding to that point. Thus, a circle, with its center at the speaker, would indicate equal radiation in all directions. Notice that at 100 cycles the sound pattern approximates this condition; at 1000 cycles (where the wavelength is about equal to the diameter of the loudspeaker). The distribution of sound shows a marked directional effect; at 2000 cycles the beam is quite sharp and is centred around the axis. The acoustical radiation pattern becomes more ''beam-like'' as the ratio of the wavelength to the diameter of the loudspeaker diminishes.

Measurements of the sound-pressure field around the human head during speech shows a similar effect;

The figure gives the sound pattern around the lips of a speaker for three bands of speech centered at frequencies of 200, 600, and 3400 cycles.



The low-pitched vowels of speech spread out quite uniformly in all directions around the head of the speaker, but the high-pitched sounds are confined to a narrow beam in front of the mouth of the speaker. It is well known that a "hiss" is a very directional.

Speech and Music

In order to predict and control the behavior of speech and music in auditoriums, theaters, music rooms, ad lecture halls, it is, of course, necessary to know the physical properties of speech and music. Thus, the characteristics which distinguish speech sounds must be known so that rooms in which these sounds are to be heard can be designed in such a way that their essential characteristics will be preserved as they are transmitted from their source to the listeners. Similarly, if a room is to be designed to enhance the beauty of music, the properties of the sounds which issue from musical instruments must be known. As we shall see, the physical properties of speech differ considerably from those of music; hence, it is to be expected that the acoustical properties of speech rooms should differ appreciably from those of music rooms.

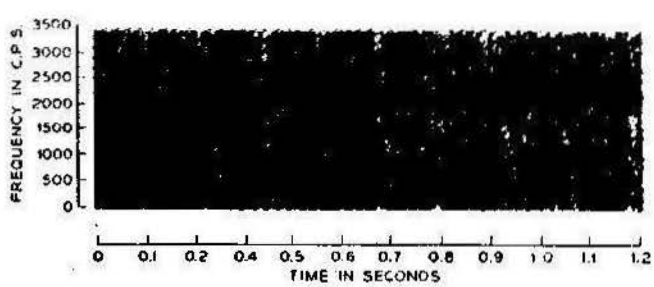
Noise, Music, and Speech

Sounds are frequently classified into three types: (a) noise (b) music and (c) speech. However, this classification is not always clear-out. It is sometimes questionable, for example, whether a sound should be classified as music or noise. In general, *noise* may be defined as *unwanted sound*. Thus, if one is listening to a concert in an auditorium, a con-

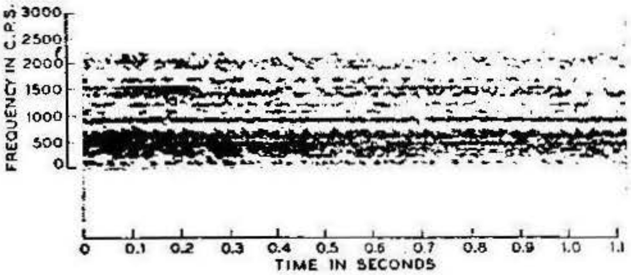
versation in the next row may be regarded as noise. On the other hand, if one is trying to converse on the telephone while "junior's rock and roll" is holding forth in the living room, this music, as far as the person on the telephone is concerned, very definitely falls under the classification of noise.

Sound may also be classified as *ordered* or *disordered*. In an ordered sound the instantaneous pressure follows a regular pattern. Furthermore, a frequency analysis of such sound will show a definite overtone structure; That is, the sound can generally be resolved into a fundamental frequency and a series of overtones, the latter having frequencies that often are integral multiples of the fundamental frequency. Overtones possessing this simple relationship of frequencies are called *harmonics*. On the other hand, the peaks of acoustic power in disordered sound (for example, the background noise in a large auditorium) occur more or less at random. In such sound, practically all audible frequencies, from the lowest or highest, are present. The periodic qualities of ordered sound are lacking.

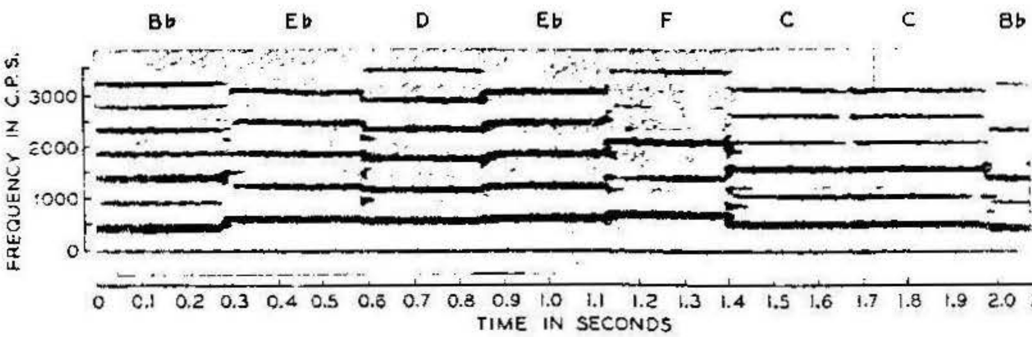
Street noise is an example of disordered sound. A spectrum analysis of this noise will show that practically all frequencies are present and that it is highly irregular in nature. This irregularity can be illustrated by means of sound spectrograms. These visual records, obtained with a sound spectrograph — an instrument developed by the Bell Telephone Laboratories — provide a frequency analysis of a sound source as a function of time. As an example, a sound spectogram of street noise in a busy city is given in this figure.



The frequency scale of the spectrogram is linear, and it covers 3500 cycles, as shown by the vertical scale to the left of the figure. The time scale is also linear and is marked in seconds along the horizontal axis. Thus, on the spectrograms, a sustained pure tone of 1750 cycles produces a single dark horizontal line mid-way between the top and bottom of the record. The greater the pressure of the sound, the darker is the line. The spectrogram of street noise shows that the peaks of power occur at random. The figure below is the spectrogram of noise from a ventilating fan. Note the regularity of the pattern and also the predominance of certain frequencies.



Music is generally, though not always, made up ordered sound. The power peaks co... at periodic intervals, as illustrated in the figure below which is a spectrogram of a portion of a clarinet solo. This record also indicates another characteristic of most musical tones. The overtone structure is harmonic. The component frequencies in this figure are integral multiples of the fundamental frequency.



Speech

The ear's sensivity is maximum in the speech frequency and normal energy range. Speech sounds vary in the length between 30 and 300 msec so that the ear perceives them individually and clearly. Speech is comprised of *phonemes,* which are individual and distinctive sounds that to an extent vary from language to language, that is, certain ones exist in one language not in another, Since certain phonemes carry more information than others, it is these which good architectural acoustics must be particularly careful to preserve intact, to preserve intelligibility. In English, consonants carry much more information than vowels, as can readily demonstrated by writing a sentence first without consonants and then without vowels:

Most speech energy is concentrated in the

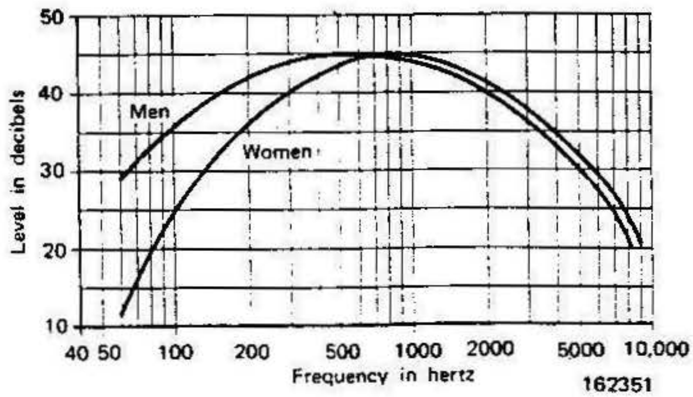
100 – to 600 – Hz range

o ee ee i oeae i e

100 – 600 e ae

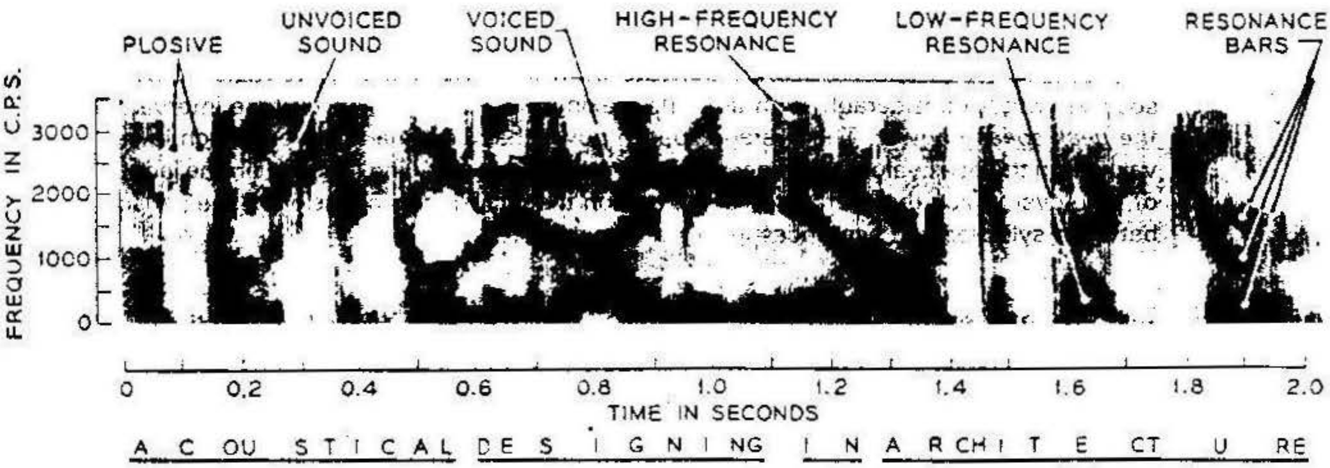
Mst spch nrgy S cncntrtd n th

100 – 600 Hrtz rng



The male voice centers its energy around 500 Hz; the female about 900 Hz. It is, however, in the high frequencies that consonants have most of their energy. Phonemes such as "s" and "sh" have most of their energy above 2 khz and both are particularly important in conveying intelligence.

Speech consists of both ordered and disordered sound. The spectrograms in this figure below illustrate the spoken words, *Acoustical Designing in Architecture*. Note that the hiss "s" in the word "acoustical" (Akussss) produces much the same record as street noise does. This "s" sound is non-periodic as contrasted with the vowel sounds, which show a definite overtone structure with the bursts of peak power coming at regular intervals of time, as shown by the vertical striations.



Nomal speech averages between 40 and 50 db sound pressure level at 3 to 4 ft, with a dynamic range of from about 30 db for a soft speech to about 65 db for loud speech at the same distance. Extremes of speech are 10 db for a whisper and 80 db for a shout, but in both these instances intelligibility is sharply reduced because of lack of consonant power. Indeed, in shouting, emphasis is necessarily on vowels so that it is generally accepted that 70 db SPL is about the upper limit of fully intelligible human speech. Note that singers who frequently exceed 90 db so at great loss of intelligibility). Another result of the high-frequency content of consonants and hence intelligibility is its directiveness. The higher the frequency the greater its directivity and the less its *diffraction* (ability to turn corners). Therefore, intelligibility of speech is greatest directly in front of the speaker and least behind him. The high-frequency tones are most easily absorbed and least reflected and deffracted.

Speech Power

The average person is surprised at the exceedingly minute amount of energy contained in speech. As mentioned in chapter I, approximately 15,000,000 lecturers speaking at the same time generate acoustical energy at a rate of only 1 horsepower. When the speech power of a single speaker is diffused in a large auditoruim, the sound pressure in the room is reduced to extraordinarily small values. Under such circumstances, it is easy to understand why it is difficult to hear well in a large room, and why very feeble sources of extraneous noise may produce serious interference with the speech. For example, the noise of a distant ventilating fan or motor, the shuffling of feet on the floor, the jarring of a nearby door, or the whispering or coughing of inconsiderate "spectators" may be sufficient to mask many of the speech sounds, and especially the feeble consonants, which reach an auditor in a large auditorium.

Since the amounts of acoustical power generated in speech are very small, the acoustics of auditoriums used primarily for unamplified speech must be carefully controlled to

make the best possible use of the usually inadequate speech power. In large auditorium, as might be expected, the amplification of speech is an indispensable requirement.

The *instantaneous speech power,* the rate at which sound energy is radiated by a speaker, varies considerably with time. Its maximum value in any given time interval is the *peak speech power.* The average speech power has, in general, a very much lower value than the peak value and depends on the method of averaging (That is, on the length of time over which the average is taken) and on the inclusion or omission of the pauses between syllables and sentences in this time interval.

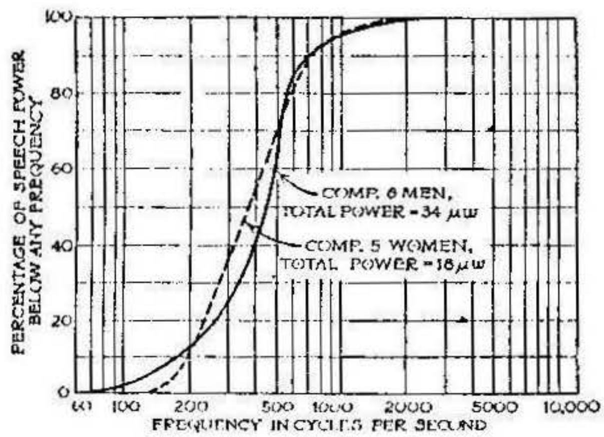
An extensive investigation of the conversational speech power output of individuals of two groups, 6 men and 5 women, was conducted by Dunn and White. "Long-time-interval averages" were obtained by averaging data over time intervals of a minute or more of continouous speech, including all natural pauses between syllables and sentences. Their results show that the long-time-interval average power output varied from one individual to another within the group of 6 men, ranging from 10 to 91 microwatts. The short-time-interval average and peak power outputs of typical speakers, speaking at a conversational level, can be and often are much higher. Calculations of these quantities were made for 1/8 second intervals, a length of time of the order of magnitude of the duration of a syllable. At least 1 percent of the 1/8 second intervals had an average power in excess of 230 microwatts for men and 150 microwatts for women, and a peak power in excess of 3600 microwatts for men and 1800 microwatts for women. This study indicates that the average male person produces a long-time-interval average sound-pressure level of about 64 db at a distance of 1 meter, directly in front of him, when he talks in a normal conversational voice; the average for women, is about 61 db at a distance of 1 meter.

The above data are for conversational speech in a quiet location in the absence of reflecting surfaces. Noise, the size of the room in which a person is speaking, his distance from the auditor, the acoustical condition of the room, and other factors affect the power a output of his speech, and especially the sound-pressure distribution throughout the room. If a noisy condition prevails, He will raise his voice in order to "override" the noise. He will, in general, increase his power output as his distance from an auditor is increased. Furthermore, it is well known that a speaker attempts to raise the power output of his voice when he is speaking in an auditorium, and the larger the auditorium, the more he exerts himself.

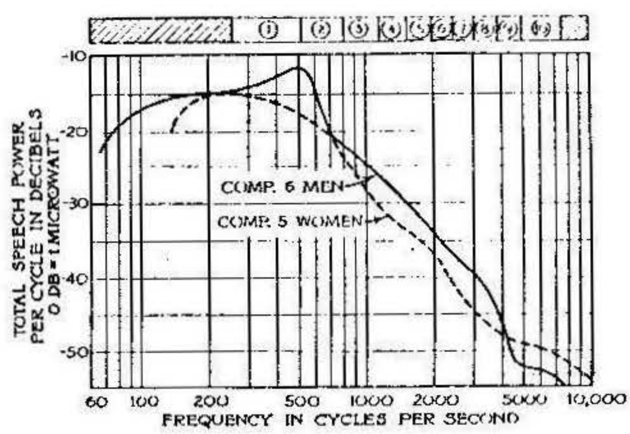
Tests conducted in a small auditorium (27,000 cubic feet) approximately 25 ft x 80 ft x 13 ft high or 8 m x 25 m x 4 m high indicate that the average speech power in this large auditorium was approximately 50 microwatts. These results confirm a reasonable expectation based upon everyday observations, namely, that a speaker increases the power of his voice in his attempt to discount the effect of the size of the auditorium in which he is speaking. He attempts to speak so that he will be heard by all auditors in the room. That he falls short of the requirements for good hearing in large auditoriums will be made manifest in the chapter on auditoriums.

The percentage of the speech power lying below a given frequency, for the average speaker is given in this figure.

The percentage of the speech power lying below a given frequency, for the average speaker is given in this figure.



There is relatively little power in the frequencies of 1000 cycles, the frequency range that characterizes most consonants. The figure below shows how the total power of average conversational speech is distributed in frequency. The level of speech power per cycle is plotted as a function of frequency. Since these curves represent data averaged over a long time interval, their shapes are affected by the frequency of occurence of the speech components as well as by their acoustic power. If these curves were "corrected" for the sensitivity of the ear so that the ordinates represented the loudness of the various frequency components as heard by the ear, the maximum would occur between 500 and 1000 cycles.



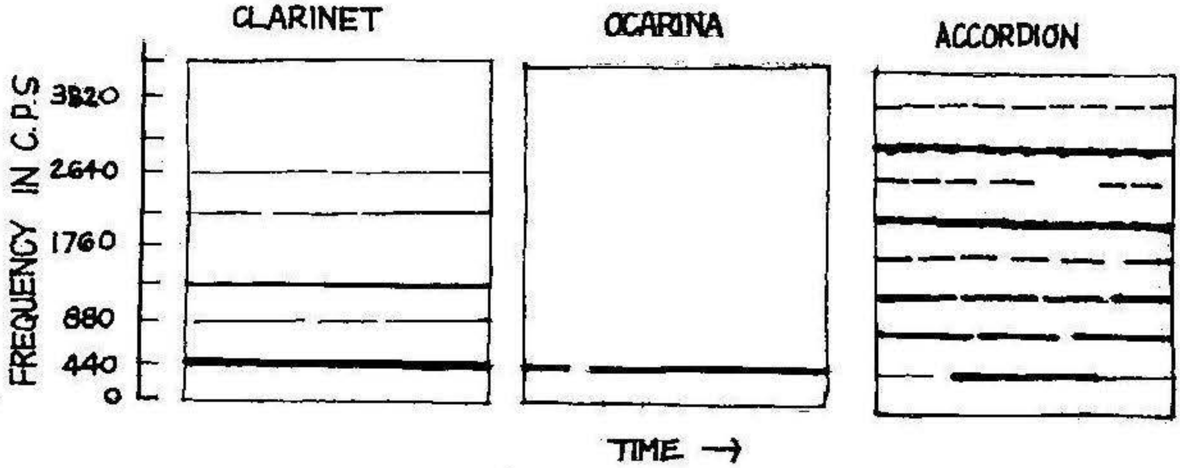
Other Sounds

Music is much broader and complex than speech in frequency and dynamic range. It has no direct parallel to intelligibility. "Reception" of music is a combination of physiological and psychological phenomena. As such, it is beyond most of the purposes of this study, but will be briefly examined in the discussion of room acoustics, auditoriums, and halls. *Noise* is variously defined as unwanted sound, sound with no intelligence content, and broadband sound depending on the listener and the situation.

Properties of Musical Sounds

The physical characteristics of musical sounds differ from those of speech in several important respects. In general, they are not so transient in nature. The separate tones of music often are sustained for an appreciable fraction of a second or longer, and the change in frequency is nearly always ordered in conformity with the relations among the frequencies which make up the musical scale. This is illustrated by a comparison of the speech spectrogram in the figure on page 53 with one of a portion of a clarinet solo, figure on page 51.

The separate tones that comprise music are in general made up not of a single simple harmonic vibration, but of long and complex series of such vibrations. In some instances, the overtones may be much more prominent from the fundamental. The number and prominence of these overtones, together with the differences in their rates of build-up and decay, are the chief determinants of the tonal characteristics of various musical instruments. The overtones from most string and pipe instrument are, at least very approximately, harmonic. The differences in the overtone structure of different musical tones on the same pitch are illustrated in the figure below.



Portions of spectrograms of sound from three musical instruments are shown. In each case the lower horizontal dark line represents the fundamental component — a frequency of about 440 cycles. Dark bands above it correspond to the harmonic overtones. Some of the harmonics are "stronger" than others, and some do not exist at all. Thus, in the clarinet solo tone the fourth and sixth a harmonics are particularly weak, and in the ocarina tone all higher harmonics appear to be absent.

The spectrogram of the accordion tone shows that its even harmonics are very weak. This record is especially interesting because it furnishes an excellent illustration of "amplitude vibrato", a rapid periodic variation in the acoustic output as a function of time.

The acoustical power generated by musical instruments; including the singing voice, is in general considerably greater than that generated in speaking. Thus, whereas the average speaker generates in the same auditorium about 100 microwatts, and often 500 to 5000 miocrowatts (see table below);

THE APPROXIMATE PEAK SOUND POWER OUTPUT OF CONVERSATIONAL SPEECH AND OF SEVERAL MUSICAL INSTRUMENTS
(Bell Telephone Laboratories)

Source	Peak Power in Watts
Conversational speech	
Female	0.002
Male	0.004
Clarinet	0.05
Bass viol	0.16
Piano	0.27
Trumpet	0.31
Trombone	6.
Bass drum, 36 in. x 15 in.	25.
Orchestra, 75 pieces	10-70

Therefore, the sound-pressure level of music in a room is usually several decibels higher than the average pressure level of speech. For this reason, less difficulty is encountered in hearing music than in hearing speech. The power generated in singing, or in the playing of musical instruments, is usually adequate for satisfactory hearing, even in auditoriums considerably larger than those in which the listening conditions for unamplified speech are just barely tolerable.

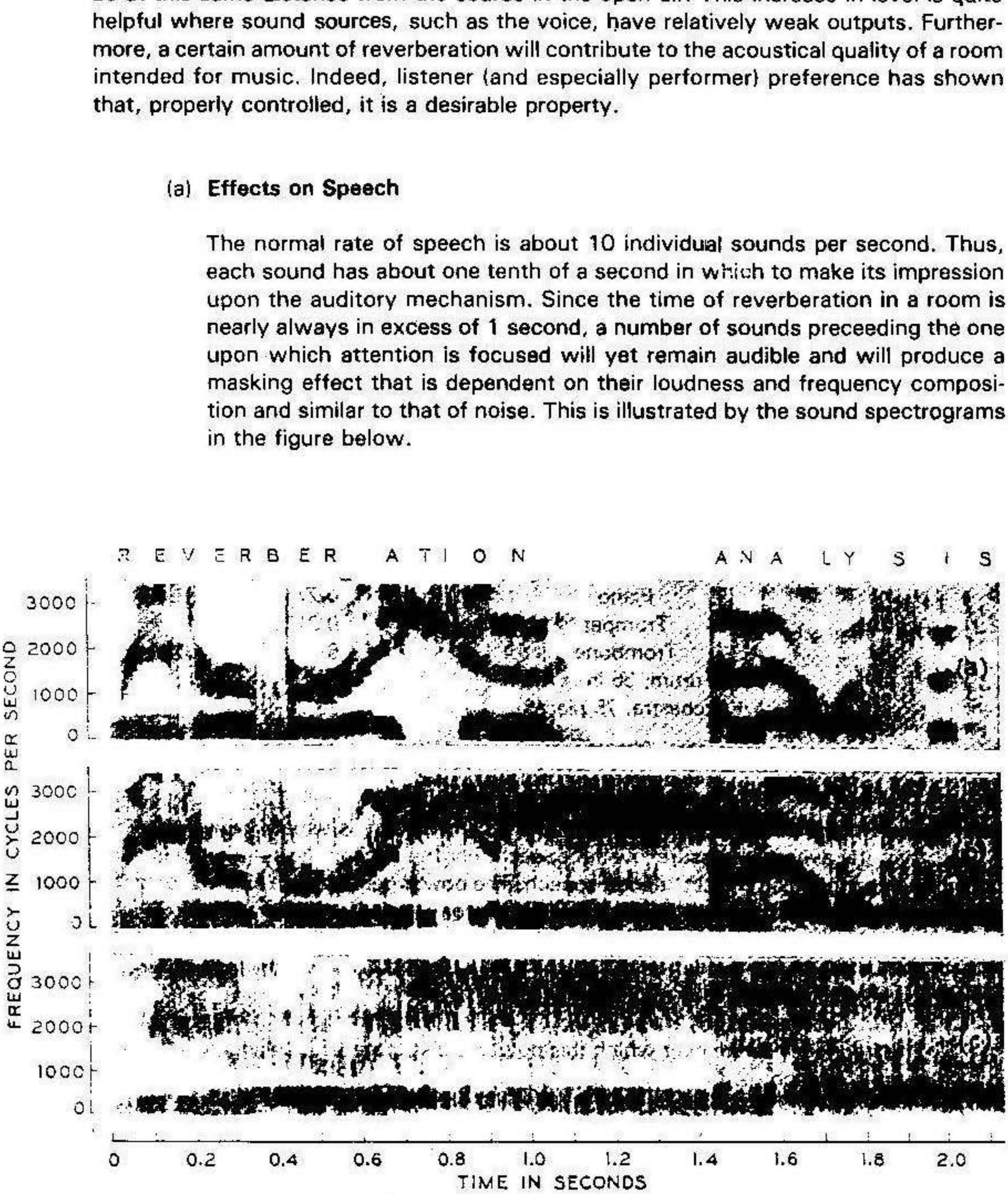
The frequency range over which this power is distributed in considerably wider than that used in speech.

Some Effects of a Room on Speech and Music

When sound waves strike the boundaries of an enclosed space they are reflected back and forth until their energy is finally dissipated. The persistence of sound in an enclosure as a result of these repeated reflections is known as *Reverberation.* This phenomenon has a very pronounced effect on both speech and music. For example, the sound pressure at a given distance from a source in a room, is, in general, greater than it would be at this same distance from the source in the open air. This increase in level is quite helpful where sound sources, such as the voice, have relatively weak outputs. Furthermore, a certain amount of reverberation will contribute to the acoustical quality of a room intended for music. Indeed, listener (and especially performer) preference has shown that, properly controlled, it is a desirable property.

(a) Effects on Speech

The normal rate of speech is about 10 individual sounds per second. Thus, each sound has about one tenth of a second in which to make its impression upon the auditory mechanism. Since the time of reverberation in a room is nearly always in excess of 1 second, a number of sounds preceeding the one upon which attention is focused will yet remain audible and will produce a masking effect that is dependent on their loudness and frequency composition and similar to that of noise. This is illustrated by the sound spectrograms in the figure below.



All three spectrograms were made from the same magnetic tape recording of the words "reverberation analysis". The record shown in the above figure (a) is a direct analysis of the original record. The next two records show the effects of adding reverberations. As a little reverberation is added, on figure (b) the individual sounds begin to overlap. After still more reverberation time of about 3 seconds — the condition for the record in figure (c) — only a few of the more prominent identifying bars of the vowels can be recognized. This record has a greater resemblance to that of street noise than it does to the original record. It is indeed remarkable that the ear can resolve, as well as it does, such a jumble of sound. But even an instrument as extraordinary as the human ear is not infallible in resolving the confusions of sounds in excessively reverberant rooms.

(b) **Effects on Music**

It is obvious that in order to preserve the original quality of a musical tone it is necessary that the relative magnitudes of all harmonic components be unaltered as they are transmitted from their source to the listeners in an auditorium. This is strictly impossible in an auditorium or in any other enclosed space. The air within the enclosure acts as if it were an assemblage of resonators that respond to certain (resonant) frequencies more than to others. Furthermore, the rate of absorption of sound by the boundaries and contents of the room, and even by the air in the room, may be greater for certain frequency components than for others. Many acoustical materials are of such a nature that the high-frequency components will be absorbed more rapidly than the low-frequency ones, and the air itself is highly absorptive at very high frequencies. For these reasons sounds at some frequencies are enhanced while others are suppressed.

It is most fortunate for the hearing of both speech and music in auditorium that these frequency distortions can be tolerated to a considerable degree of without sacrificing the characteristics that are essential for the correct auditory recognition of sounds of speech or for the enjoyment of music. Thus, one is able to recognize a given sound when it is spoken by different men women even though the frequency spectra of this sound, as spoken by these individuals, may be quite different. Except for the absorption in air, frequency distortion of the above types is not encountered outdoors.

Music in the open, however, lacks the beneficial effects of reverberation; also, the loudness level may be too low for optimum listening conditions. It is apparent from the foregoing qualitative considerations of the effects of enclosures on speech and music that the acoustical properties of rooms are greatly dependent on such factors as noise, reverberation, loudness, and room resonances. These factors will be considered qualitatively in subsequent chapters, where general principles will be described to guide the architect and the engineer in the acoustical designing of all speech and music rooms.

NOISE CRITERIA

Negative Effects of Noise

Although noise effects and their control are discussed in the later chapter on Noise Control, noise criteria and their background are discussed here as part of the overall study of hearing and sound sources. There are two basic approaches to the negative effects of noise, a psychological practical one and a purely physiological one. The latter is concerned with the physical impact of noise on the body including hearing loss and other deleterious conditions (see high noise levels in the next pages.)

The former is concerned with noise levels that cause annoyance and disturbance to daily activities including work, relaxation, and rest, and is discussed herein below.

Noise and Annoyance.

Tests have shown that in general, annoyance, (which is subjective and psychological) as a result of noise is:

(a) Proportional to the loudness of the noise
(b) Greater for high-frequency than low-frequency noise
(c) Greater for intermittent than continuous noise
(d) Greater for pure-tone than for broadband noise
(e) Greater for moving or unlocatable (reverberant) noise than for a fixed-location sound.
(f) Much greater for an intelligence-bearing noise (neighbor's radio) than for a no-sense noise.

In order to establish criteria ~~for acceptable~~ background noise, certain of these effects must be neglected for the sake of simplicity.
We thus ignore:

factor (c) since design is based on continuous sounds

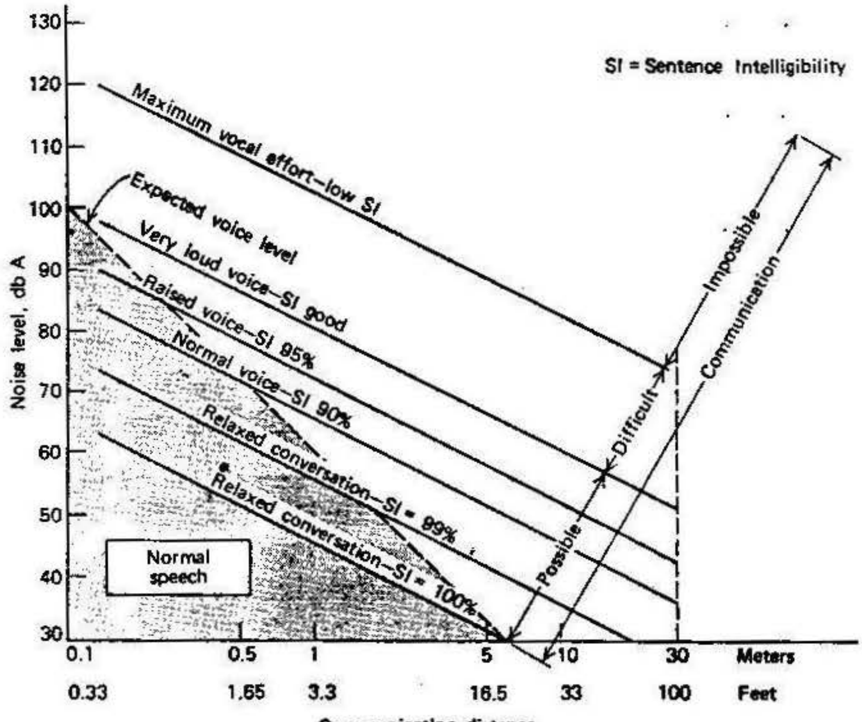
factor (d) since broadband noise is assumed

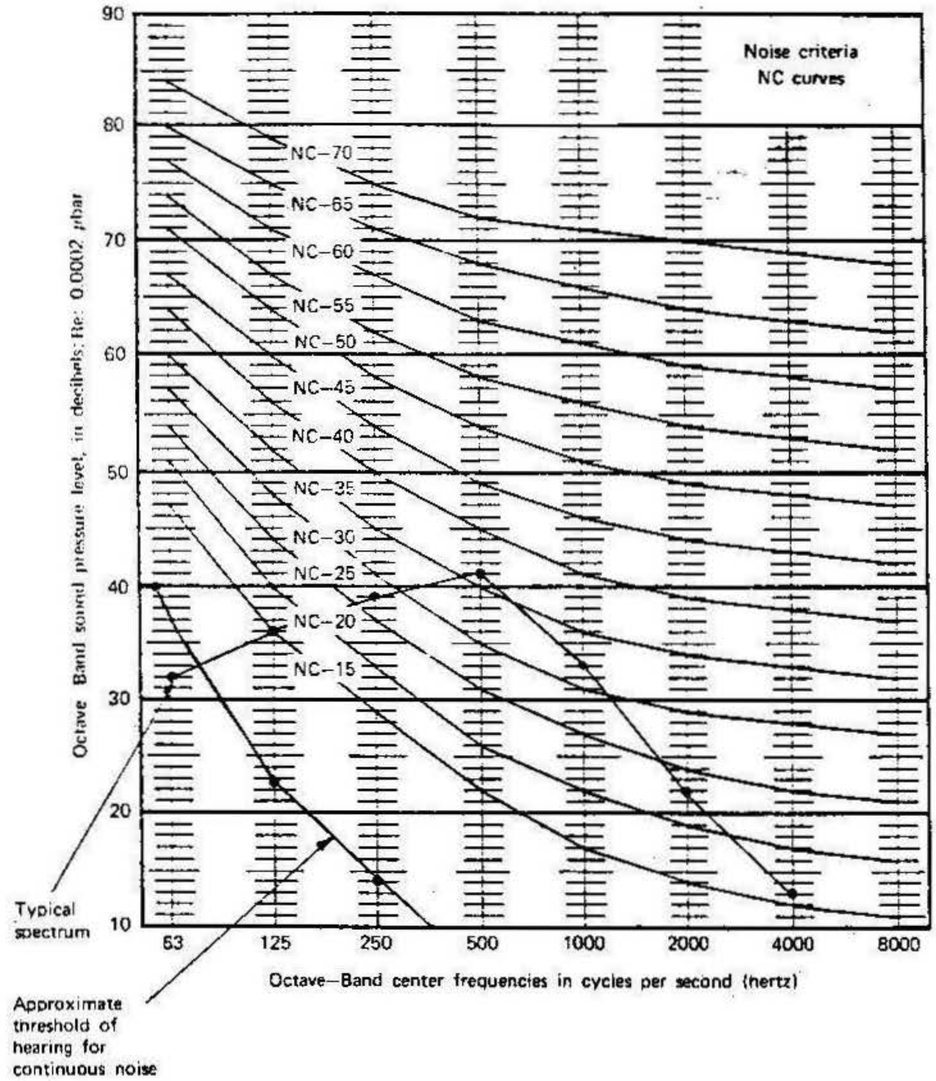
factor (e) since the noise source is assumed to be fixed in location

factor (f) since we consider noise level rather than content

Thus the particularity and special characteristics of noises such as a barking dog (c), a whistle (d) a single passing vehicle (e), and intelligible sounds (f) are not considered. Consideration of the remaining factors (a) and (b) or interference with speech communication resulted in concepts called the Articulation Index (AI) and Speech Interference Level (SIL). This was determined by reading a carefully selected Set of Phonetically balanced in the nonsense syllables to a test audience in the presence of different levels and compositions of background noise.

The ratio of correct answers to total syllables was the Articulation Index. An Articulation Index[11] in excess of 0.5 indicated a condition in which perfect intelligibility could be expected. A simplified Version of the AI called the Speech Interference Level (SIL) was devised by Beranek. The SIL consists simply of the arithmetic average in decibels of the background — noise sound levels in three octave bands, 600 to 1200, 1200 to 2400, and 2400 to 4800 Hz, since it was found that correlation between intelligibility and the sound power in these three bands could be established. The results of this and similar studies are shown in this figure and the table.

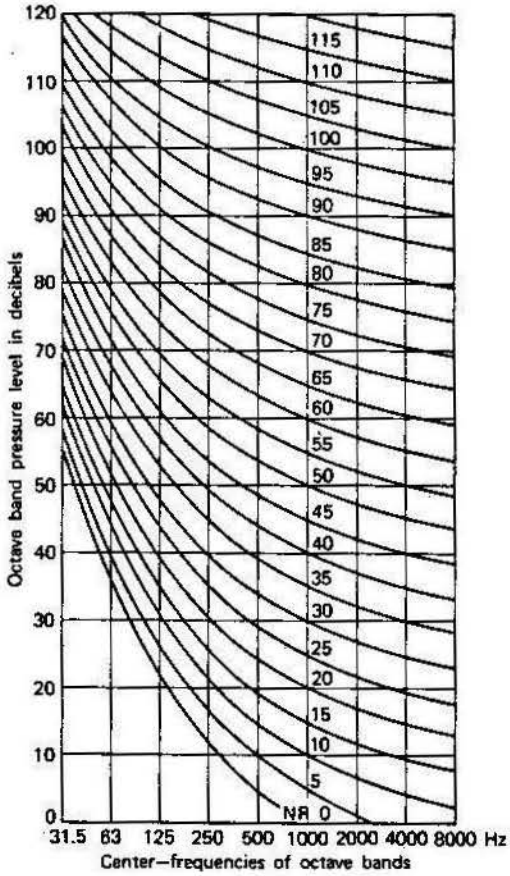




On the basis of SIL data and loudness level (LL) Information, Banadek developed the well-known and widely accepted Noise Criteria (NC) curves shown in this figure.

These curves take cognizance of the field-determined fact that most people prefer to speak at a level no greater than 22 phons above the background noise by combining the SIL levels in decibels with this fact, the NC curves are derived, that is, they represent a loudness level 22 phons higher than the SIL in db. These contours represent then the maximum *continuous* background noise that will be considered acceptable in the environment specified and correspond fairly accurately to background noise level in commercial environments. A similar set of curves called Noise Rating (NR) curves has been proposed by the International Standards Organization (ISO), see figure below.

These curves are less stringent than NC curves in the low frequency and more stringent in the high frequencies.



In application, the octave-band spectrum of a noise over the range of 63 to 8000 Hz is measured and plotted on an NC curve sheet. The lowest NC curve that is not exceeded by any portion of the plot is the NC rating of the noise. Thus a specification of maximum noise levels of NC-30 means that no portion of sound power level of any continuous background noise in the area may cross the NC-30 contour. Conversely, a piece of equipment rated NC-35 has an octave-band spectrum completely below NC-35.

4 ROOM ACOUSTICS

SOUND IN ENCLOSURES

When a continuous sound is generated in an enclosure, fields are set up as described in chapter 3 (sound fields in an Enclosed Space). When the sound is not a continuous tone or noise but a series of discrete sounds, following one upon the other and containing intelligence, as in speech or music, the room must be designed to maintain and enhance this intelligibility. That is what is meant by design of room acoustics.

The generated sound radiates out from the source until it strikes a room boundary or other large surface. Before reaching this surface the sound intensity is attenuated by distance (inverse square law) and by absorption in the air. This latter is only appreciable in large rooms, and at frequencies above 2000 Hz. When the sound reaches the wall it is partially reflected and partially absorbed. A small portion is also transmitted into adjoining spaces. The energy transmitted is so small that it has little effect on the space within which the sound originates although, as will be discussed on the chapter of Building Noise Control. It may be very important in the surrounding spaces.

The ratio between the energy absorbed and reflected will significantly affect what one hears within the space. Specifically, if little energy is absorbed and much is reflected, two effects will be noticeable. Intermittent sounds will be mixed together (which may make speech less intelligible or music more pleasant), and steady sounds will accumulate into a reverberant field, making the space "noisy". Conversely, if much energy is absorbed and little reflected, the room will sound quiet to speech and "dead" to music.

Sound Absorption

It is useful to express the above effects quantitatively. Most materials are neither perfect reflectors nor perfect absorbers. The coefficient of absorption (α) is defined as:

$$\alpha = \frac{I_a}{I_i}$$

Where I_i = intensity impinging on the material, watts/cm^2
I_a = intensity absorbed by the material, watts/cm^2
α = absorption coefficient (no units)

Thus α is a measure of absorption efficiency. If α =1.0 all the impinging energy is absorbed. Since open space has this characteristics, α has also been defined as the ratio between the absorption of a given material and that of an open window of the same area. Obviously then for an open window,

$$\alpha = 1.0$$

The total absorption (A) provided by a surface (S) is expressed in sabins, as

$$A = S\alpha$$

where A = total absorption; sabins
S = surface area, square feet
α = coefficient of absorption

Since α is a ratio and this unitless, and S is square feet, $S\alpha$ should be in square feet. Actually, sound absorption units are called sabins in honor or W.C. Sabine, a pioneer in architectural acoustics.

Most rooms are constructed of several materials, each having different absorption coefficients α and thus it becomes necessary to use.

$$\Sigma S\alpha = S_1\alpha_1 + S_2\alpha_2 + \cdots\cdots S_n\alpha_n$$

$$\text{or} \quad \Sigma\bar{A} = \bar{A}_1 + \bar{A}_2 + \cdots\cdots + \bar{A}_n$$

WHERE $\Sigma S\alpha$ = the total absorption in the room, sabins

$S_1 S_2$,etc = the areas (ft^2) of each material

α_1, α_2,etc. = the coefficients of each materials

$\bar{A}_1$, $\bar{A}_2$, etc. = total absorption of each different material

Room absorption is discussed in detail in chapter 9 on Air-borne Noise Reduction.

Reverberation

Reverberation is the persistence of sound after the cause of sound has stopped — a result of repeated reflections. Reverberation time (T_R) describes the period required for the sound level to decrease 60 db after the sound source has stopped producing sound. For most rooms, the reverberation time are specific frequency may be found by the formula:

$$T_R = K \times \frac{V}{\Sigma S\alpha} \text{ sec}$$

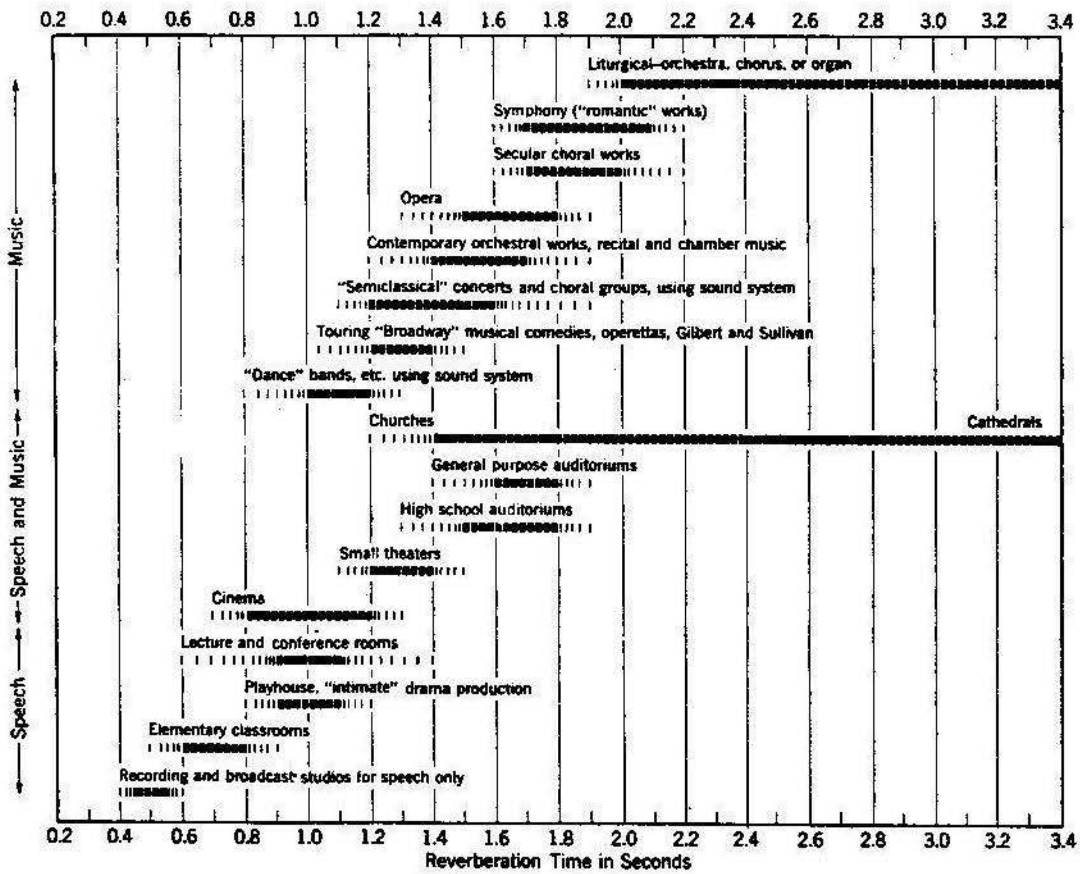
where K = a constant, equal to 0.049 when V is in cubic feet and 0.16 when V is cubic meters

V = room volume, ft^3, (m^3)

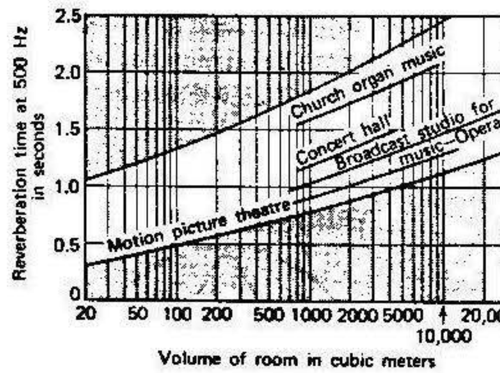
$\Sigma S\alpha$ = total absorption, sabins at the frequency.

In most room acoustic studies, reverberation times are calculated at 125, 500, 1000, and 2000 H_z, although the mid-frequency (500 to 1000 H_z) range is generally the reference used in specifying the reverberation time of a room.

Reverberation can be considered as a mixture of previous and more recent sounds. The converse of reverberation or reverberance is articulation. An articulate environment keeps each sound event separate rather than running them together. Spaces for speech activities should be less reverberant — more articulate — than those designed for performance of romantic music. The figure below compares the reverberance and articulation requirements of performance activities and spaces.



In the next figure below, it shows average optimum reverberation time for various types of auditoriums as a function of size. The values are average because recommendations vary as much as 100% between respected sources. In addition to an optimum reverberation time in the central 500-H_z 1-kh_z range, the reverberations at other frequencies should exhibit a slight drop in the higher frequencies and a rise at the lower frequencies to compensate for the sharp drop in ear sensitivity. Thus T_R at 100 H_z should be, according to most authors, between 25 to 50% longer than T_R at the center frequencies. As a matter of interest, concert halls judged to be excellent by musical experts have a center frequency reverberation time between 1.6 and 1.8 sec.



Reflection and Diffraction of Sound in Rooms

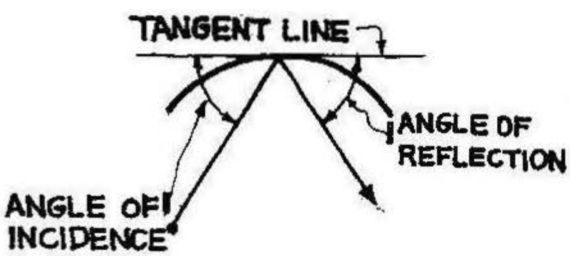
When a sound wave impinges on a non-yielding wall, part of the incident sound is reflected from the wall; another part is transmitted into the wall, where some of it is dissipated as heat; and the rest is transmitted through the wall. For example, if the wave encounters a wall of very porous material, such as mineral wool, that portion of the wave which is transmitted into the wall suffers considerable attenuation as it is propagated through the material. Although this reduction in sound intensity is due largely to the viscous losses within the capillary pores of the material, the vibration of the fibers of the material often contributes to the attenuation.

Most wall structures are not non-yielding; they vibrate as a whole, or in parts, under the action of the pressure pulsations of incident sound waves: The wood, plaster, or even masonry walls of a room are set into vibration, like diaphragms, and hence radiate sound energy. Since most of the sound that is communicated from one room to an adjacent one is transmitted in this manner, rigid, heavy walls should be better insulators of sound than flexible, light ones; and experience gives abundant evidence that they are. One of the most effective means for providing a high degree of sound insulation makes use of a combination of rigid partitions and porous materials.

The relative magnitudes of the absorbed, transmitted, and reflected components of a sound wave incident on a wall depend on such factors as the frequency and angle of incidence of the sound wave, the nature of the wall material, and the manner in which the wall is supported, reinforced, backed.

The Reflection of Sound

When a "free" sound wave (one free from the influence of reflective surfaces) strikes a uniform surface that is large compared to the wavelength of the sound, the reflection of the wave is similar to the familiar reflection of light. Suppose that the path of this sound wave is represented by a *ray* along which the wave advances, that is, by a line perpendicular to the advancing wave front. Then, by the *law of reflection*, the angle of reflection for this ray equals the angle of incidence, and the reflected ray lies in the plane of incidence. Thus in the figure (a) below, which represents reflection from a plane surface, $<i = <r$. When this law is applied to the analysis of reflection from curved surfaces; the curved surface being regarded as made up of many small plane surfaces, the character of the reflections from a concave or convex surface can be derived as shown in the figure (b) and (c).



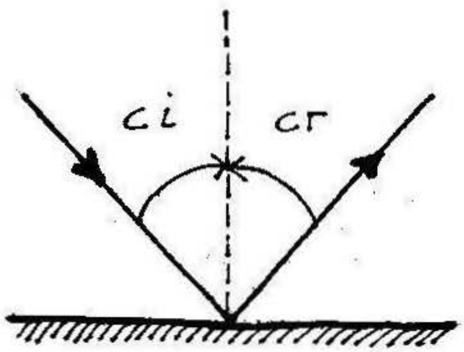
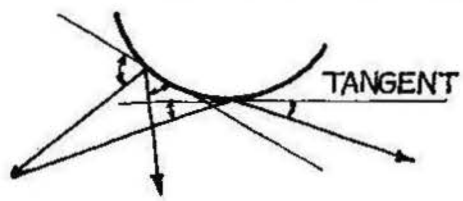


FIG. (a) REFLECTION FROM A PLANE SURFACE



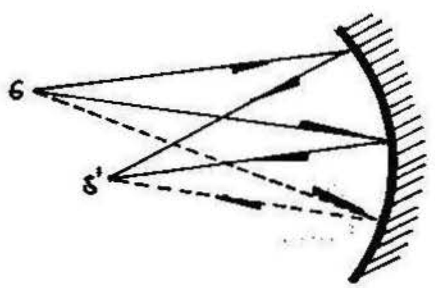


FIG. (b) REFLECTION FROM A SPHERICAL SURFACE

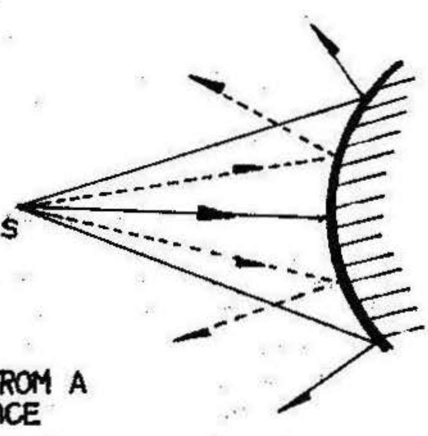
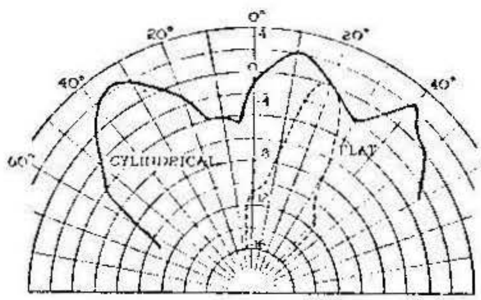
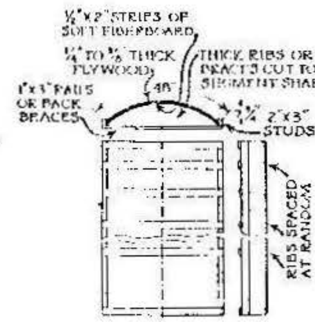


FIG. (C) REFLECTION FROM A CONVEX SURFACE

Evidently, as shown in figure (b), a concave surface tends to concentrate the reflected waves. Large concave surfaces may be used to advantage as reflectors, but if used indiscriminately they may ruin the acoustics of a room. The reflective properties of concave surfaces will be discussed on the chapter (Acoustical Design of Rooms). Occasionally the reflections from such surface are beneficial, but more frequently they are deleterious. On the other hand, since a convex reflector (fig. c) tends to "spread" the reflected waves, convex surfaces at the boundaries of a room tend to diffuse the sound throughout the room. For this reason a number of radiobroadcasting studies and other special room have been constructed with cylindrical convex panels as part of the wall construction. Their action is dispersing sound waves is illustrated in the figure below.



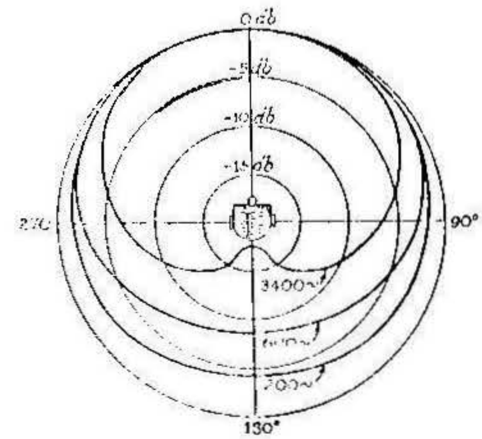


Diffraction of Sound

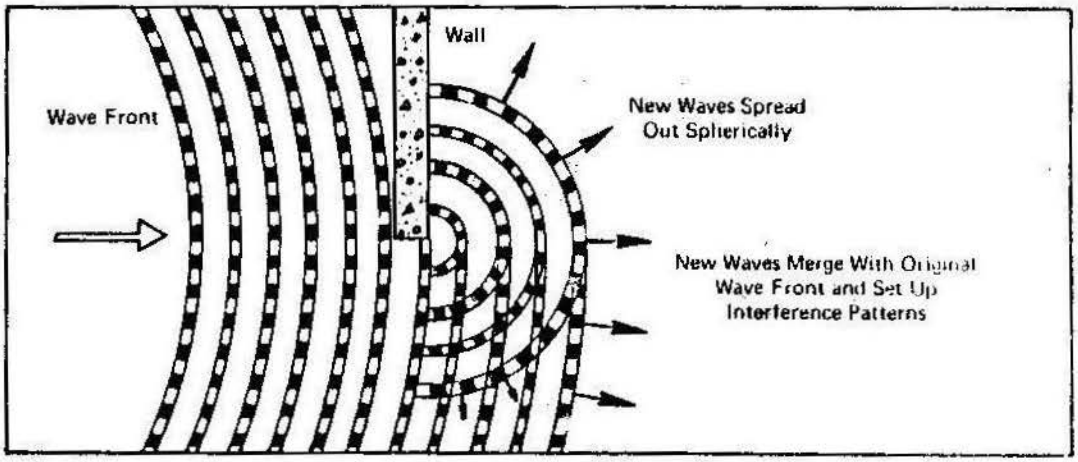
In the preceding sections there have been discussed many of the basic principles of sound, such as reflection, transmission, and absorption all of which have analogies in the subject of light. The assumption that light is propagated in straight lines gives rise to that branch of optics called *geometrical optics,* and this "rectilinear" propagation accounts for the sharp shadows and images that can be formed by light. For example, light coming through a small opening such as a crack in a door is confined to a narrow beam of about the same shape and cross-sectional size as the opening. *Geometrical Optics* corresponds to *geometrical acoustics,* which assumes that sound is propagated in straight lines; it is valid only for wavelengths that are short compared to the dimensions of rooms and the openings and reflecting surfaces in them. It should be remembered that many surfaces in rooms are not large in comparison with the wavelengths of low-pitched sounds. Windows, doors, pilasters, beams, coffers, any form of relief ornamentation, and patches of absorptive material — all introduce *diffraction* which greatly alters the direction and magnitude of the reflected sound. *Physical optics* and *physical acoustics* are based upon wave properties and thus, describe many aspects of light and sound that cannot be handled by a geometrical treatment; among these, diffraction is the most important.

When sound comes through a crack in the door, it spreads out almost uniformly; or when sound encounters the corner of a building, it bends around the corner. In such instances, we say the sound has been diffracted or bent. Diffraction is the change in direction of

propagation of sound waves due to their passage around an obstacle. The extent of the diffraction depends on the relationship between the wavelength of the sound and the size of the obstacle. This is illustrated in the figure below, which gives the sound-pressure distribution around a person's head while he is speaking.



It will be seen that at low frequencies there is approximately equal radiation in all directions, whereas at higher frequencies, where the wavelength is much shorter and the bending is much less, the distribution is fairly directional. Similarly, sound from a point source reflected from a hard parabolic surface can produce a concentrated "beam" which converges to a focus or which diverges very little if the wavelength of the sound is small compared to the dimensions of the reflector, it will be relatively ineffective in its influence on the sound waves. As a further illustration of diffraction, the figure below represents plane waves striking the edge of a partition. Notice how the waves, travelling from left to right, are bent around the edge of the obstacle

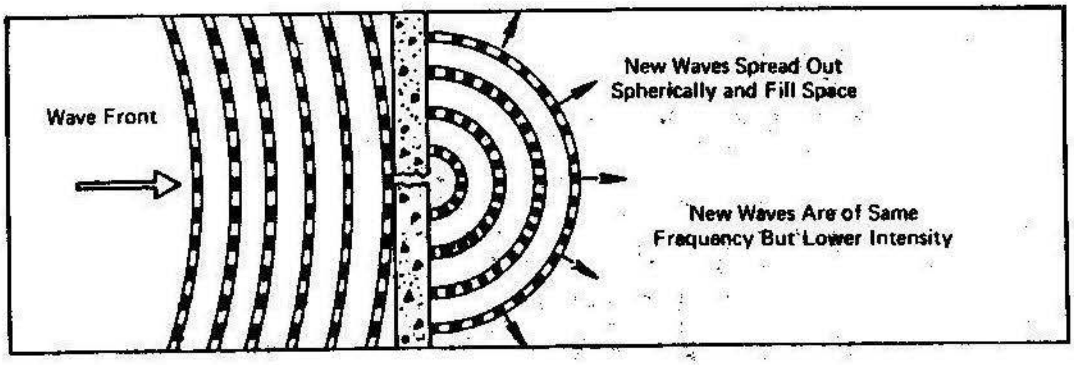


diffraction of plane waves at the edge of a partition

It would appear that, in regard to diffraction, light and sound behave very differently. However, both theory and experiment show that sound and light behave very much alike if the openings and obstacle in the sound field are in the same proportions to the wavelengths of sound as the openings and obstacles in the light field are to the wavelength of light. Visible light wavelengths of the order of 0.000015 to 0.000030 inch, whereas audible sound has wavelengths of the order of 0.06 to 60 feet. It is principally because of this great disparity in the wavelengths of the sound and the light that we usually observe that light travels in straight lines through openings and past obstacles, whereas, sound spreads out very considerably under similar circumstances.

Diffraction of Sound Transmitted Through Openings

An elementary principle of physical acoustics, known as Huygens' principle, enables us to determine the extent of spreading of a sound wave when it is transmitted through an opening of known size. Consider a plane wave falling upon a very large surface in which there is an opening that is small in comparison with the wavelength of the sound. A familiar example is a small hole in a door, as illustrated in the figure next page.



Diffraction of sound passing through a small opening.

According to Huygens' principle, which states that each point of the wave front at any instant may be regarded as a source of secondary waves, the opening O may be regarded as such a source from which the sound spreads out as a spherical wave. Hence, whereas the supposed wave was plane before it reached the small opening, it emerges approximately as a spherical wave and thus diverges widely. If the opening is large compared to the wavelength of the sound propagated through it (for example; a large proscenium), there is only slight bending near the edges.

Since the wavelength of sound vary from about 0.06 to 60 ft, the diffraction may be pronounced for some frequencies and neglible for others. For example, a 3-feet door opening would be small compared to a wavelength of 60 feet. Therefore, such a low frequency sound would be very much diffracted in going through the door, the emergent sound spreading out almost uniformly in all directions. In contrast, this same door opening would be very large compared to a wavelength of 0.06 foot (a frequency of about 19,000 cycles), and therefore a sound having such a wavelength would be transmitted through the door with little diffraction. Obviously, sounds such as those in speech and music, which are made up of a wide range of frequencies, are selectively diffracted because the low-frequency components will diverge widely while the high-frequency components will continue in a relatively narrow beam.

Diffraction of Sound from Reflective And Absorptive Surfaces

In architectural acoustics the diffraction effects that accompany the reflection of sound are even more important than those that accompany the transmission through openings. The architectural and decorative treatment of rooms, such as beams, columns, and ornamental plaster, results in regular or irregular breaks or dicontinuities in the boundaries of the room, and consequently the interiors of most rooms are of such a nature as to introduce complicated diffraction phenomena. As an instance of how sound is reflected and diffracted from a broken surface, such as the coffers in a ceiling, a spark photograph obtained from a model of an auditorium is shown in this figure.

The diffraction of sound from the projecting ribs is similar to that already described for the transmission of sound through small openings: the edges of the ribs of the coffers are small in comparison with the wavelength, and in accordance with Huygens' principle these edges diffract and thus diffuse the sound.

Discontinuities in the sound-absorptive treatment of a wall (such as "patches" of absorptive materials), as well as irregularities in the shape of the wall (such as bumps) will diffract sound waves that strike them. Thus, patches of absorptive material on the walls of a room diffract or scatter incident sound waves and aid in diffusing the sound throughout the room. Since a certain degree of diffusion of sound within a room is a desired condition for good acoustics, this subject will receive more detailed discussion in the chapter of ("Acoustical Design of Rooms").

Diffraction from an obstacle in the path of a sound wave is frequently referred to as *scattering.* The obstacle alters the sound fields in its immediate neighborhood; the alteration (that is, the difference between the existing wave and the wave which would exist if the obstacle were absent) is called the *scattered wave.* Despite the complicated nature of this type of diffraction, certain properties of diffraction are worth remembering.

(1) When an obstacle is large in relation to the wavelength of the incident sound, a sharp "shadow", similar to a light shadow is cast;

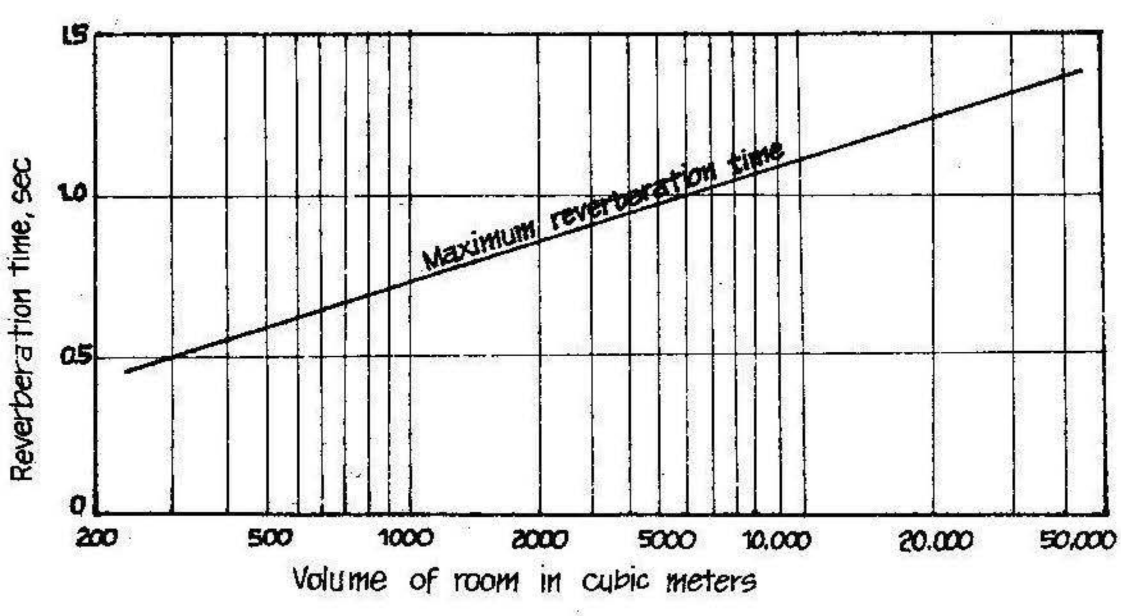
(2) When an obstacle is small in comparison to the wavelength of the incident wave, the sound is scattered in all directions;

(3) When the size of the obstacle is comparable to the wavelength, the sound is scattered in a complex but regular pattern, which depends on such factors as the shape, size, and absorptive properties of the obstacle and wavelength of the sound and its direction of propagation with respect to the obstacle.

A number of scattering effects are illustrated in the photographs in this following figure. The pictures show plane sound waves of a very high frequency travelling from left to right in water, striking solid steel cylinder whose cross section appears as a dark circle. In (a) the cylinder has a diameter equal to twice the wavelength of the sound waves; in (b) the diameter is equal to 8 wavelengths. The larger cylinder casts a much more pronounced shadow than does the smaller one. Scattering due to obstacles within a room and to wall surface irregularities is very important in contributing to the uniformity of the sound field within the room.

Criteria for Speech Rooms

The overriding criteria for speech is intelligibility. Since speech of short disconnected sounds, among which are high-frequency, low-energy phonomes, the ideal room must assure the ears reception of these phonomes as they are given. Since a slow decay rate is the equivalent of a masking noise, reverberation must be kept to a minimum. Maximum T_R is given in this figure, as determined by one well-known source.



Too low a reverberation time (very high absorption, minimum reflection) is also undesirable because:

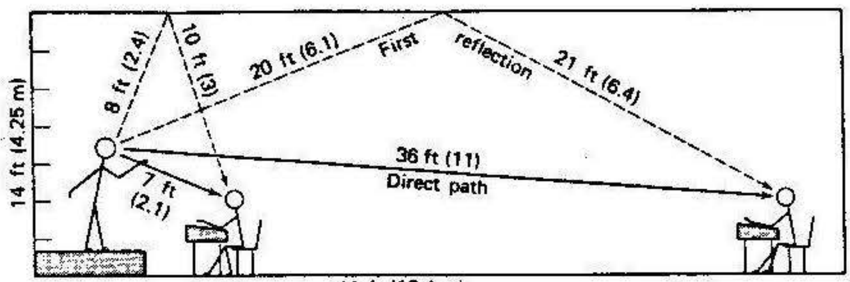
(a) It limits the size of the room to that which can be covered by direct sound only.

(b) It is disturbing to the speaker since absence of reflection prevents him or her from gauging proper voice level and tends to cause excessive effort (shouting).

Thus proper design of a room for speech is a compromise between the the need for some reflection and the desire to minimize reflection to preserve intellibility.

Another important factor must be considered. The reflections associated with reverberation can have either a salutory or a deleterious effect. The ear cannot distinguish between sounds that arrive within a maximum of 50 msec ± of each other. Sounds arriving within this time reinforce the direct path signal and appear to come from the source. Sounds arriving after this time are apprehended as a fuzzy echo or elongation of the sound, reducing intellibility and directiveness. Since 35 msec corresponds at 344 m/sec to 12 m. or 40 ft., the room must be so arranged ~~that the~~ difference between the first reflection path and the direct path is no greater than 40 to 55 ft. or 12 to 17 m.

See figure below.



Optimum *reverberation* for speech is shown in the equation.

$$T = 0.3 \log \frac{V}{10}$$

Where T = time in seconds
V = room volume in m^3

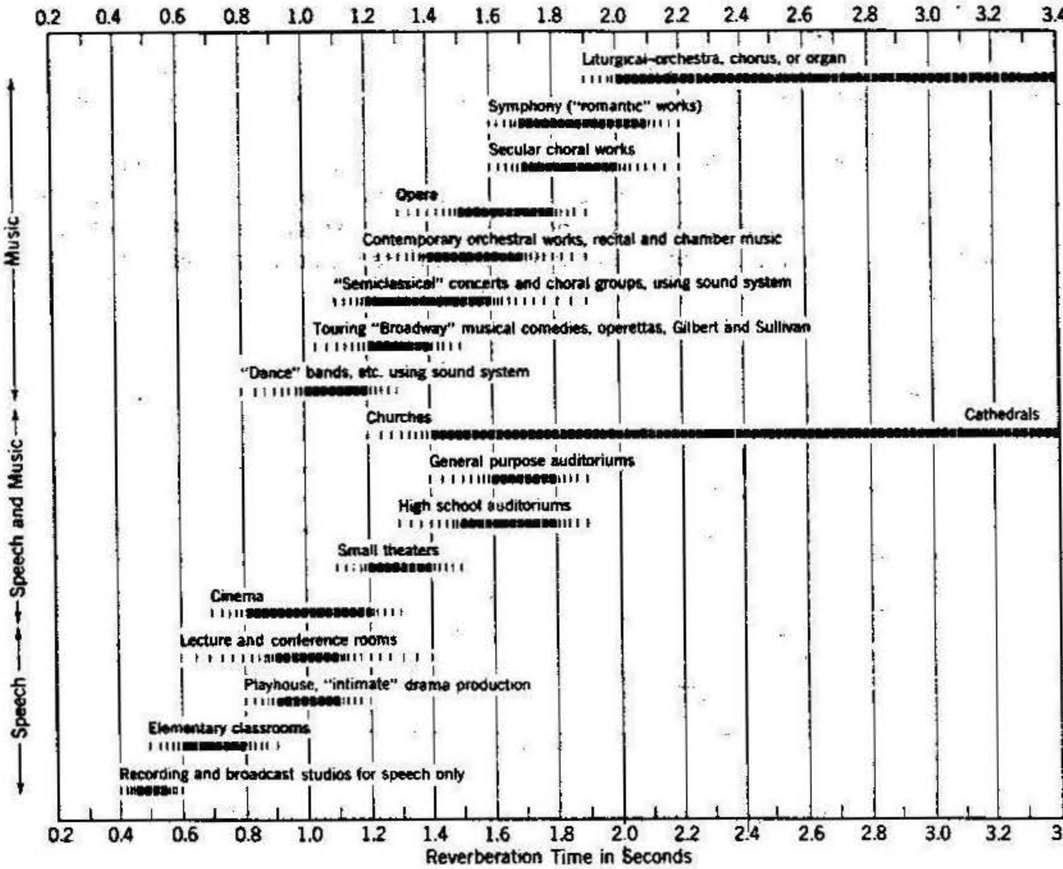
A good figure for lecture rooms is between 0.35 and 0.4 sec.

Criteria for Music Performance

Adequate design for a music space requires recognition of the following:

(a) Large-volume spaces require direct-path sound reinforcement by reflection.

(b) Relatively long reverberation time is needed to enhance the music — the exact amount depending on the type of music. This reverberance must, however, not include clear echoes.



(c) Directivity declines if the reinforcing signal is excessively delayed. With large ensembles, directivity gives the sense of depth and instrument location necessary for proper appreciation. This is often referred to as clarity or definition in music. With a solo instrument this problem is diminished.

(d) Brilliance of tone is primarily a function of high-frequency content. Since these frequencies are most readily absorbed, a good direct path must exist between sound source and listener. Since our eyes and ears are close together, a good sound path exists when a good vision path exists. At the other end of the spectrum, lack of sufficient bass expresses itself as a loss of "fullness", which is often caused by resonant absorption.

The actual design of music performance space is a very complex procedure involving extensive calculations of absorption, reverberation time and ray diagramming, and juggling of materials, dimensions, and wall angles. Simulation techniques and acoustics are models are also employed. Most modern design also uses movable reflector panels and other active variables. After construction is completed extensive tests are conducted and field adjustments are made.

Ray Diagrams and Sound Paths

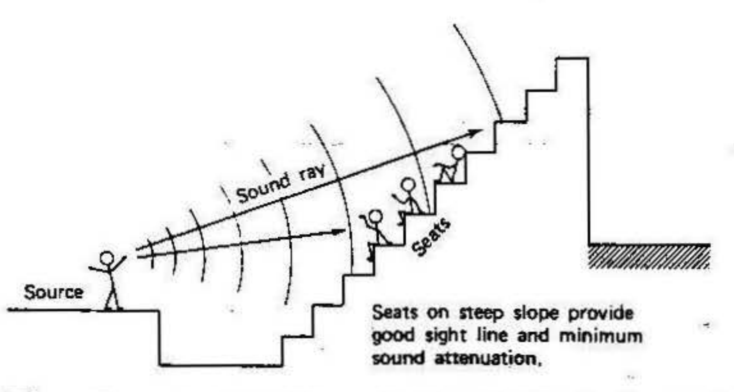
Ideally, every listener in a lecture hall, theater, or concert hall should hear the speaker of performer with the same degree of loudness and clarity. Since this is obviously impossible by direct-path sound, the essential design task is to plan methods for reinforcing desirable reflections and minimizing and controlling undesirable ones. Normally, only the first reflection is considered in ray diagramming, since it is strongest. Second and subsequent reflections are usually attenuated to the point that they need not be considered except for the special situations of flutter, echoes, and standing waves.

(a) Reflections

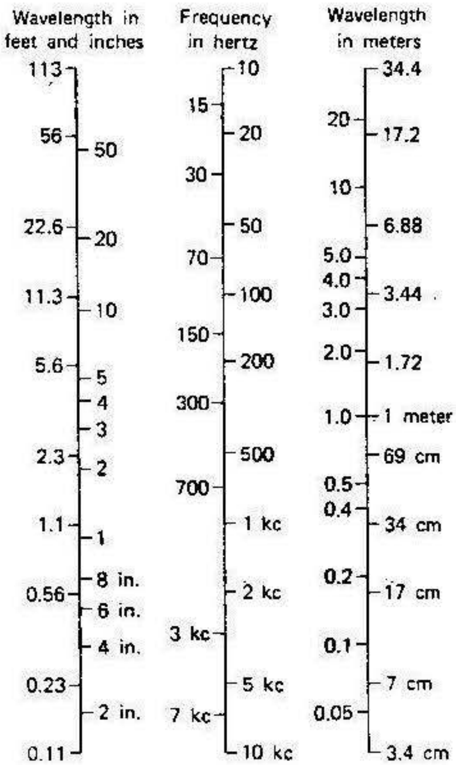
These occur when sound hits a surface that is neither predominantly absorptive nor sound transparent at the specific frequency. Non-absorptive surfaces that are large, as compared to the wavelength at a given frequency, reflect sounds. Thus, 3-inches wide pickets in a fence reflect frequencies with wavelengths that are less than three in (4500 H_z and higher). If the fence is 50% open, it reflects about 50% of the high-frequency energy. However, it does not significantly affect the lower frequecies. These lower frequencies (longer wavelengths) simply diffract around the obstruction.

(b) Specular Reflection

Specular reflection occurs when sound reflects off a hard polished surface. This characteristics can be used to good advantage to create an effective image source. In ancient greek and roman theaters, seats were arranged on a steep, conical surface around the performer. The virtue of the arragement in the fig. (a) below is that the sound power travels to each location, with minimal attenuation.



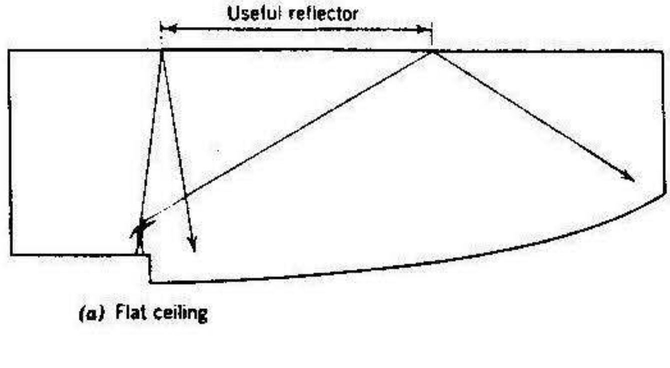
This is not practical physically, but it can be accomplished effectively by the use of a reflecting panel (see figure).



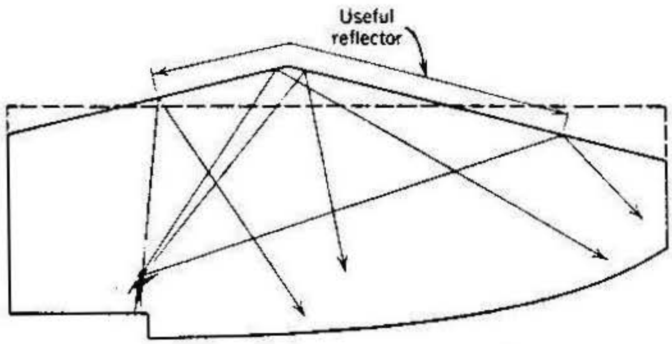
Panel dimension must be at least one wavelength at the lowest one frequency under consideration. The next figure is a conversion chart from frequency to wavelength in feet and meters.

(c) Ray Diagrams

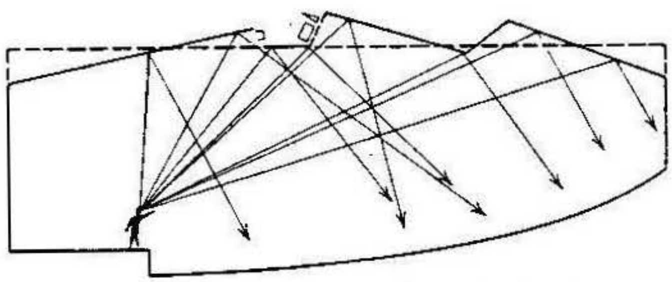
Ray diagramming is a design procedure for analyzing reflected sound distribution throughout a hall, using the first reflection only. Ray diagram is shown in the following figure.



(a) Flat ceiling

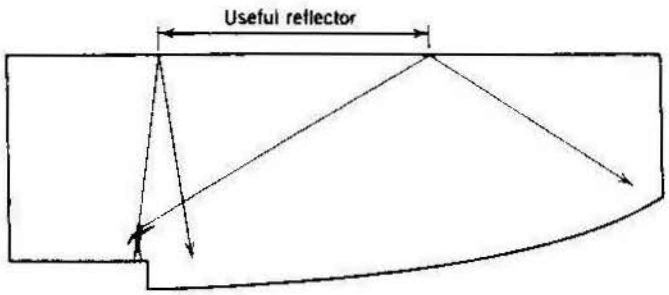


(b) Two panel ceiling increases useful reflecting area



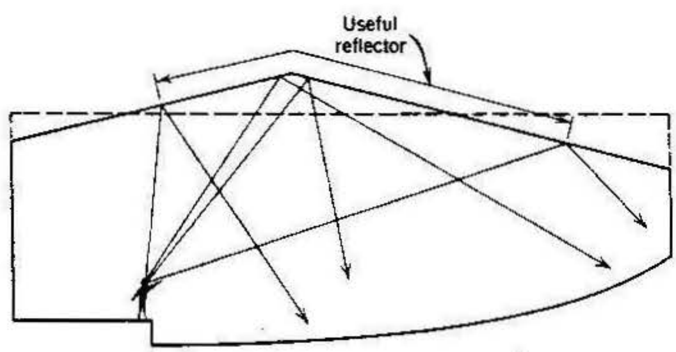
(c) Multifaceted ceiling incorporates lights and loudspeakers

The rays are drawn normal (perpendicular) to the spherically propagating sound waves. Specular reflection is assumed, that is, the angles between the reflecting panel and the incident and reflected rays are always equal. Thus, in addition to the direct sound, each listener is receiving reflected sound energy. It is as though there were additional sound sources. The real one and numerous image sources. Figures (a) (b) and (c) next page show the application of a ray diagram to a lecture hall.



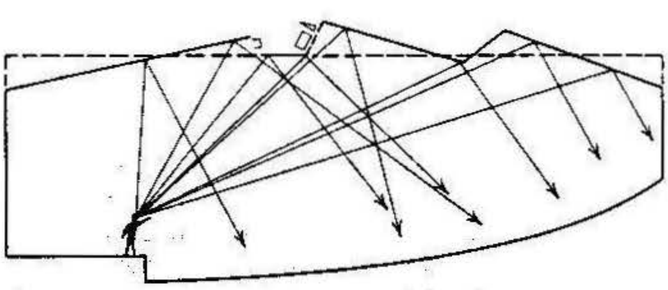
(a) Flat ceiling

In figure (a) the stage height and seating slope are arranged to provide good sight lines, and the ceiling height is established by reverberation requirements, aesthetics, costs, etc. It can be seen that less than half of the ceiling is providing useful reflection. By dividing the ceiling into two panels



(b) Two panel ceiling increases useful reflecting area

figure (b), people in the rear of the room perceive the direct source plus two image sources, and the useful reflecting area is increased by 50%.



(c) Multifaceted ceiling incorporates lights and loudspeakers

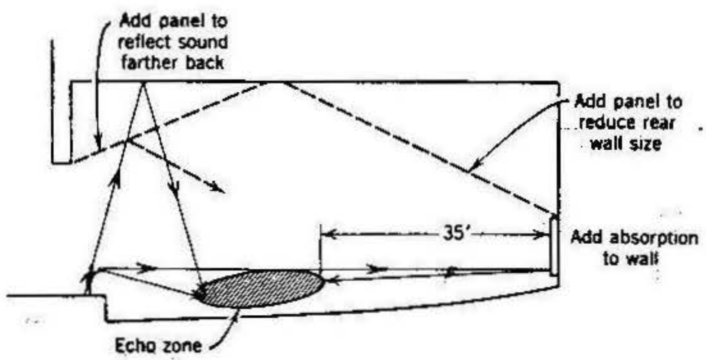
In figure (c), the shape has been further refined to include a lighting slot and loudspeaker grille.

(d) **Echoes**

A clear echo is caused when reflected sound at sufficient intensity reaches a listener approximately 70 msec or more after hears the direct sound. This occurs whenever the reflected sound path is more than 70 ft. longer than the direct path.

Echoes even if not distinctly discernable are undesirable in rooms. They are annoying and make speech less intelligible. the relative annoyance is dependent on the time delay, and loudness relative to the direct sound which, in turn, are dependent on the size, position, shape, and absorption of the reflecting surface.

Typical echo-producing surfaces in an auditorium are the back wall and the ceiling above the proscenium. The figure below shows these problems and suggests remedies. Note that the energy that produced the echoes can be redirected to places where it becomes useful reinforcement. If echo control by absorption alone were used on the ceiling and back wall, that energy would be wasted. The rear wall, since its area cannot be reduced too far, may have to be made more sound-absorptive to reduce the loudness of the reflected sound.

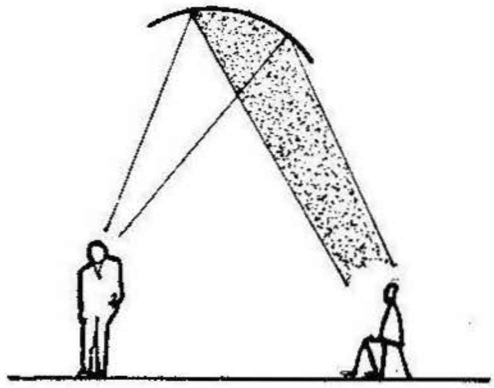


(e) **Flutter**

A flutter is perceived as a buzzing or clicking sound, and it is comprised of repeated echoes traversing back and forth between two non-absorbing parallel (flat or concave) surfaces. Flutters often occur between shallow domes and hard, flat floors. The remedy for a flutter is either to change the shape of the reflectors, their parallel relationship, or add absorption. The solution chosen will depend on reverberation requirements, cost, or esthetics.

(f) **Focusing**

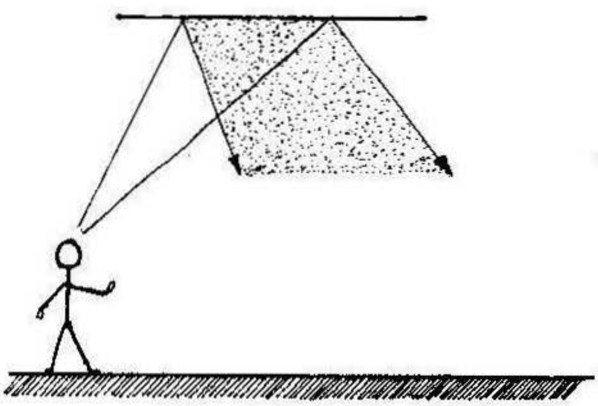
Concave domes, vaults, or walls will focus reflected sound into certain areas of rooms. This has several disadvantages. For example, it will deprive some listeners of useful sound reflection and cause hot spots at other audience positions.



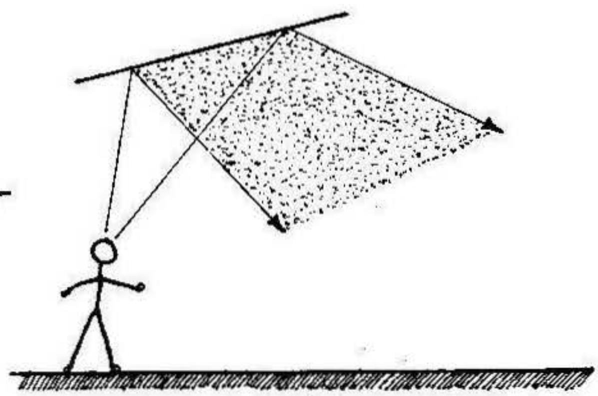
(a)

(g) **Diffusion**

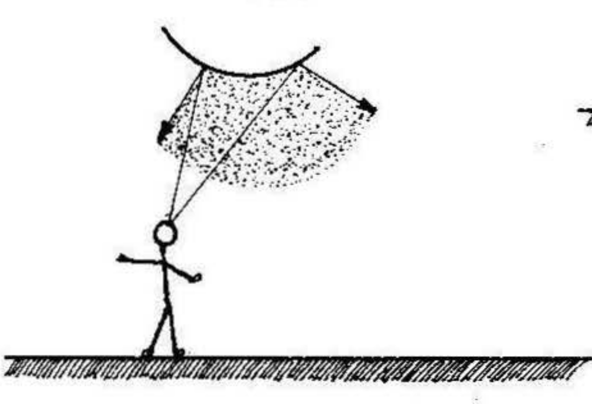
This is the converse of focusing and occurs primarily when sound is reflected from convex surfaces. A degree of diffusion is also provided by flat horizontal inclined reflectors as shown.



(a)



(b)

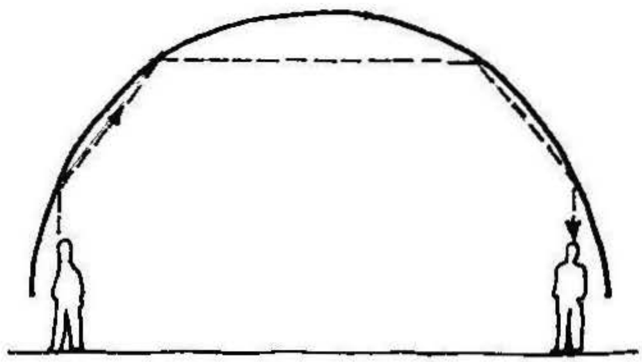


(c)

In a diffuse sound field the sound level remains relatively constant throughout the space and as such is extremely desirable for musical performances.

(h) **Creep**

This describes the reflection of sound along a curved surface from a source near the surface. Although the sound can be heard at points along the surface, it is inaudible away from the surface.



CREEP
(b)

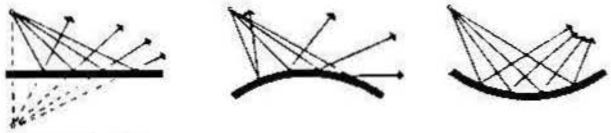
(i) **Standing Waves**

Standing waves and flutters are very similar in principle and cause, but are heard quite indifferently. When an impulse (such as a hand) is the energy source, a flutter will occur between two parallel walls. When a steady pure tone is the source, a standing wave will occur, but only when the parallel walls are spaced apart at some integral multiple of a half wavelength.

When the parallel walls are exactly one-half wavelength apart, the tone will sound very loud near the walls and very quiet halfway between them. This is because at the center, the reflected waves travelling in one direction are exactly one-half wavelength away from those travelling in the other, and thus equal *opposite in pressure,* which results in total cancellation. In other rooms standing waves are noted as points of quiet and maximum sound in the room. Standing waves are important only in rooms small with respect to the wavelength generated (smallest room dimension, <30 ft. for music or <15 ft. for speech.

Another effect of standing waves, or *resonance* is the accentuation of the particular frequency, which will cause a standing wave in a room of that dimension. Thus, if one speaks (or plays a musical instrument) standing near a wall of a room, about 8 ft. $\times$ 8 ft. (2.40 $\times$ 2.40m) one would notice an abnormal and sometimes unpleasant loudness in the sound at about 280 H_z.

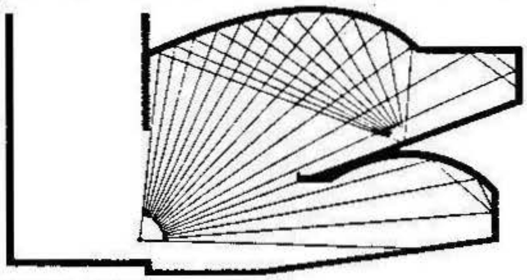
Thus, when a musician plays a scale, one note may seem far louder than the adjacent ones, and listeners in one section of the room will hear a different quality of sound than those in other sections. This effect must be avoided for music performance but is merely an annoyance in rooms designed for speech use. This is one of the reasons that one finds music rehearsal rooms, broadcast studios, etc. with nonparallel walls and undulating ceilings; these irregularities direct sound energy toward the absorbing materials of the room and cause the standing waves to degenerate.



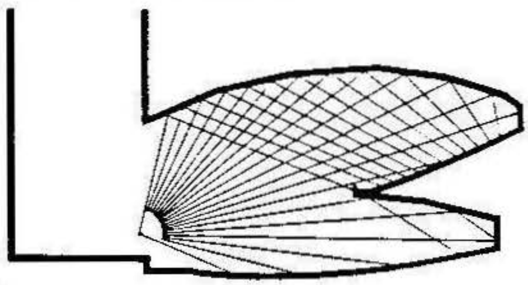
Law of reflection

shape of plane	level	convex	concave
secondary sound ray	reflected	dispersed	focused
divergence	unchanged	greater	smaller

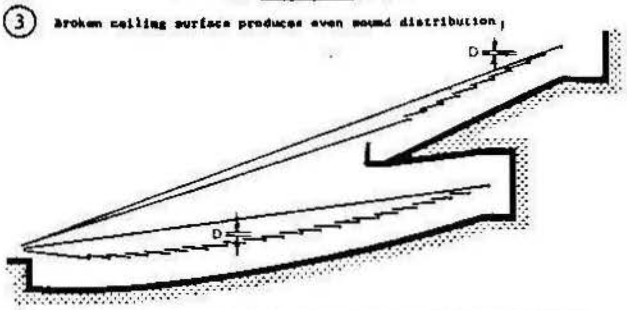
(1) Depending on shape of incident plane, sound rays are reflected as follows:



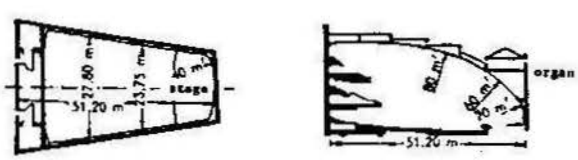
(2) Concave ceiling is acoustically bad



(3) Broken ceiling surface produces even sound distribution



(4) Arrangement of seating which ensures unobstructed paths for direct sound. Step height D 8 cm constant.



(5) Plan and section of concert hall (Salle Pleyel, Paris, 1927)

Good audibility is essential in spaces designed for theatrical and musical performances: it is achieved when sound is everywhere audible unchanged (without echo) and with a suitable reverberation period.

Audibility is affected by:

1. Shape of room
2. size of room
3. room furnishings
4. position of source of sound
5. reverberation period.

1. **Shape of room** (in plan) preferably rectangular or trapezoid in direction of sound, → (5). Square, circular or oval shapes, etc, are acoustically unfavourable. Large curved areas produce focal points, and large overhangs screen path of sound: both are detrimental to good hearing conditions, → (2), (3). Provision of stepped seating is advantageous; breaking wall and ceiling surfaces produces even sound distribution.

2. **Room size**: normal speech is audible for a distance of about 20–30 m (65–100 ft) in direction of speech; 13 m (43 ft) to side of speaker, and 10 m (33 ft) behind speaker. Max cubic space content without use of aids (loudspeakers, reflectors, etc) should not exceed 18 000 m^3 (630 000 ft^3) for speech and 30 000 m^3 (1 000 000 ft^3) for music. Height should not exceed 8 m (26 ft).

Where possible, height : width : length ratio should be 2 : 3 : 5; 1 : $\sqrt[3]{2}$: $\sqrt[3]{4}$; 'Golden Section', i.e. 3 : 4 : 8.

3. **Room furnishings and finishings**: in general, solid roofs and walls are less satisfactory than suspended ceilings and claddings with intervening voids which will resonate with the sound (wood, Celotex, etc). In design of heating and ventilation systems avoid rising warm air currents between source of sound and listener. Absorbents should be provided on rear walls near back seats on dome surfaces and on solid balcony railings, etc, → p. 64 (3).

Seating should be staggered and rising. According to French Standards, stepping of seating by 80 mm ($3\frac{1}{4}$ in) ensures direct sound to all seats, → (4). In UK 100 mm (4 in) is normally allowed.

4. **Position of source of sound** should be in front of a hard reflecting surface and, where room height is excessive, reflective sounding boards above sound source are recommended.

Where there is more than one source of sound, each must be sufficiently close to the other; loud-speakers in same room as source of sound should be ⩽ 34 m (112 ft) and 24 m (80 ft) away from sound for theatrical and musical performances respectively.

5. **Reverberation time**: reverberation is caused by reflection of direct sound from wall and ceiling surfaces, → (1). This should be registered by listener as gradual dying down of sound.

5

ACOUSTICAL PROPERTIES OF BUILDING MATERIALS

ABSORPTION

The rate which sound is absorbed in a room is a prime factor in reducing noise and controlling reverberation. All materials used in the construction of buildings absorbed some sounds, but proper acoustical control often requires the use of materials that have been especially designed to function primarily as sound absorbs. Such materials are popularly known as "acoustical" materials. These are also used for reduction of noise in office buildings, hospitals and restaurants.

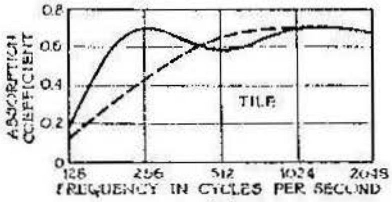
Many people tolerate noise, but most people do not like it. This probably is the reason why many business establishments have found that the cost of acoustical treatment usually is more than offset by the profit resulting from the increase in patronage after the installation of the absorptive material. When properly planned. The absorptive treatment of rooms contributes to good acoustics making it possible for speech to be enjoyed to the fullest extent.

It is always necessary to choose materials with proper acoustical characteristics, but this is not enough. All other physical and decorative properties of the materials must be given proper attention. Having determined which materials have the required absorptive properties, the architect must raise about each material such questions as the following: Is it combustible or fire-resistant? How much light will it reflect? What about its structural strength, absorption of water, and attraction for vermin (rats)? How foolproof is it? Can its application be entrusted to the average journeyman? What is its appearance, and what are its decorative possibilities? How much does the material cost? Will it be expensive to install and maintain?

How Sound is Absorbed

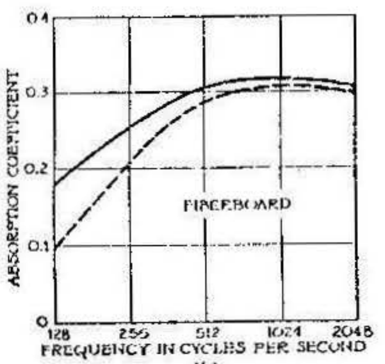
Sound is absorbed by a mechanism which converts the sound into the other forms of energy and ultimately into heat. Most manufactured materials depends largely on their porosity for their absorptivity. Many materials, such as mineral wools pads and blankets, have a multitude of small deeply penetrating intercommunicating pores. The sound waves can readily propagate themselves into these interstices, where a portion of the sound energy is converted into heat by frictional and viscous resistance within the pores and by vibration of the small fibers of the material. If the material is sufficiently porous, and of appropriate thickness, as much as 95 percent of the energy of an incident sound wave may be absorbed in this manner.

When sound waves strike a panel, the alternating pressure of these waves against the panel may force it into vibration. The resulting flexural vibrations use up a certain amount of the incident sound energy by converting it into heat. If the panel is massive and stiff, the amount of acoustical energy converted into mechanical vibrations of the panel is esceedingly small; on the other hand, if the panel is light and flexible, the amount of energy absorbed may be very large, especially at low frequency.



(a)

For example, the figure shows that fiberboards such as Masonite, and acoustical tile such as Acousti-celotex are much more absorptive at frequencies of 128 and 256 cycles when they are nailed to wood strips — and can vibrate as panels — than when they are cemented or other wise fastened against a rigid surface. Plaster on lath over studs provides much more absorption at low frequencies than does the same type of plaster applied directly to solid masonry walls. In general, the rate at which a flexible panel absorbs acoustical energy of vibration, to its lternal damping coefficient, and to the frictional losses at the edges of its mounting.

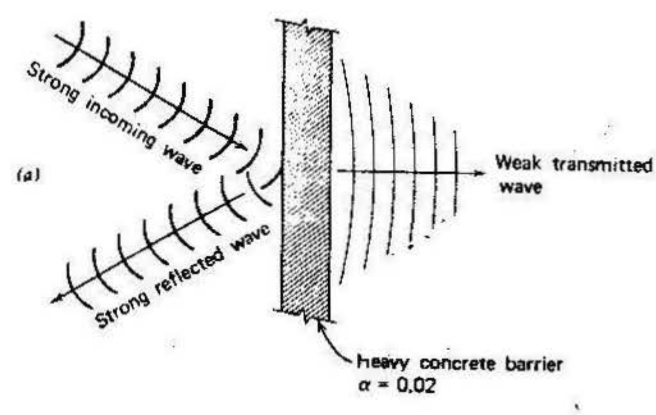


(b)

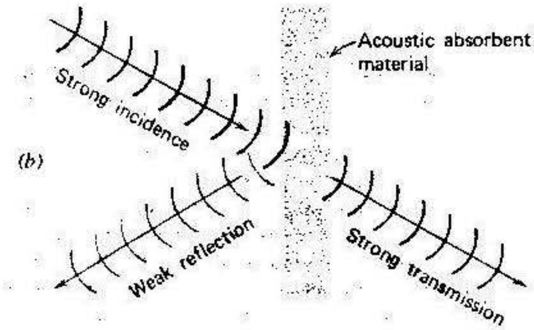
Absorption by porous materials normally is large at high frequencies and small at low frequencies. Absorption by panel vibration is small at high frequencies but may be large at low frequencies. Both of these types of absorption are important in the control of sound in rooms. By using them in the proper proportion, it is possible to control the absorption of sound throughout the audible range of frequencies. This because a necessity in sound recording and radio studios and is often desirable elsewhere.

Mechanics of Absorption

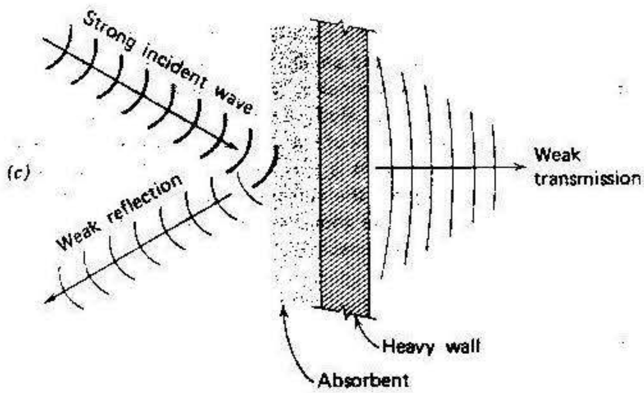
We have already learned the definition of sound absorption of sound in the last chapter and its relevance to room reverberation characteristics. Re-examining absorption as an acoustic phenomenom, we refer to the figure below so that we may understand the application of absorption material. Refer to the figure (a) below



(a) Action of an incoming sound wave striking a heavy barrier. Much of the energy is reflected, some is absorbed, and a little is transmitted.

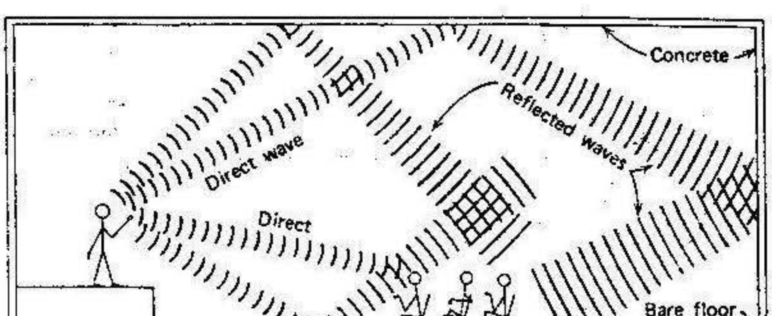


(b) Action of acoustic absorbent material alone. Very little energy is reflected, some is absorbed, and most is transmitted.

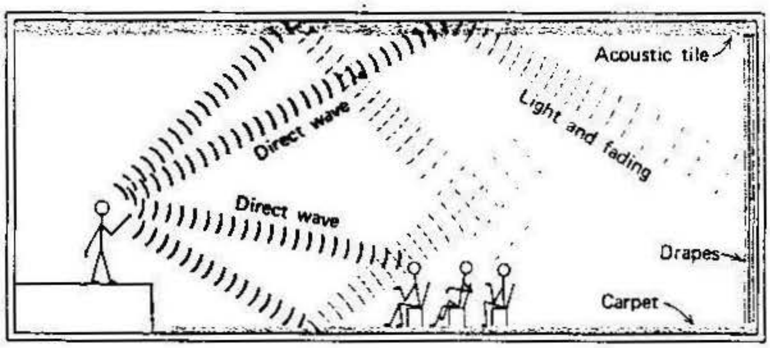


(c) When absorbent is applied to the heavy wall, it "traps" sound preventing reflection, while wall mass acts to reduce transmission.

In an untreated room of normal construction, when the sound waves strike the walls or ceiling, a small portion is absorbed and most of the sound is reflected. The exact proportions abviously depends on the nature of construction. When acoustical figure (c) above, some of the energy in the sound waves is dissipated before the sound reaches the wall. The transmitted portion is slightly reduced but the reflection is greatly reduced. The difference between the two situations is shown graphically in this figure



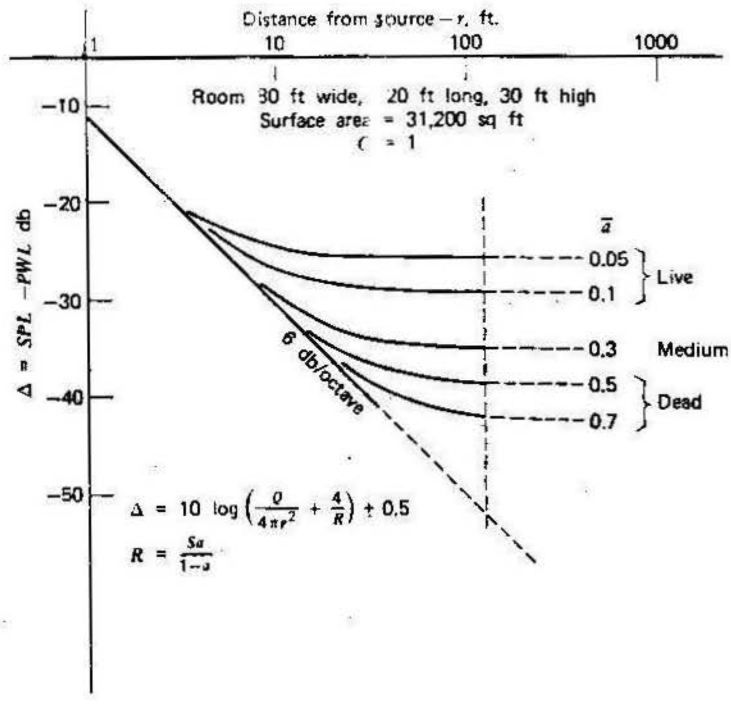
(a)



(b)

In the untreated space (a) reverberant (reflected) sound constitutes the greater portion of received sound in much of the room. these reflections are largely eliminated in (b) by wall and ceiling absorption. Note that direct wave is completely unaffected.

Referring to the figure below, the result of adding absorptive material to a room is shown in greater detail.



Subjective Loudness Changes and Corresponding Intensity Level Changes

Change in Level, Decibels	Subjective Change in Loudness
3	Barely perceptible
6[a]	Perceptible
7	Clearly perceptible
10	Twice or half as loud
20	Four times or one-quarter as loud

[a]Six decibels correponds to the change encountered when distance to the souce in a free fields is doubled (halved).

Here, the result of adding absorptive material to a room is shown in greater detail. The difference between a room with average absorption of 0.1 and the same room with б/a of 0.7 is 15 db, which is a reduction in loudness of approximately one and half times.
See table

We will now examine the acoustic materials themselves and the effect of varying type quantity, thickness, and installation methods.

Absorptive Materials

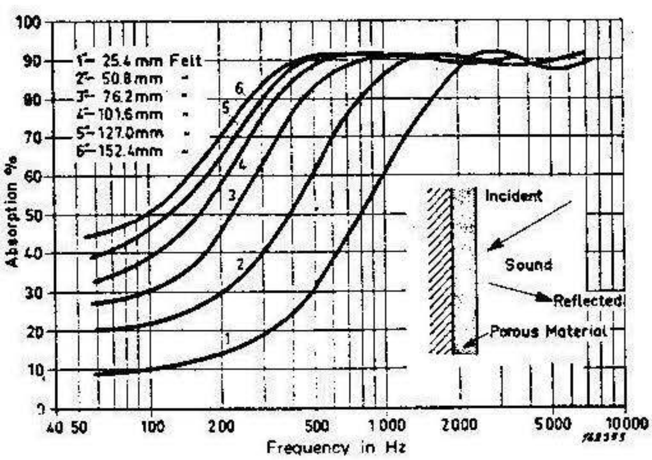
There are three families of devices for sound absorption –

(a) Fibrous materials
(b) Panel resonators
(c) and Volume resonators

All types absorb sound by changing sound energy into heat energy. Only fibrous materials and panel resonators are used commonly in buildings. Volume resonators are used principally as enclosures for absorbing a narrow band of frequencies.

The "FIBROUS" material or porous absorb the frictional drag produced by moving the air in small spaces within the material. The absorption provided by a specific material depends on its thickness, density, and porosity and resistance to air flow. For example, materials must be thick to absorb low frequency sound effectively. Since the action depends on absorbing energy by "pumping" air through the material, the air paths must *extend from one side to the other.* A fibrous material with sealed pores is useless as an acoustic absorbent (Therefore, painting will generally ruin a porous absorber). A simple test is to blow smoke through the material. If the smoke passes through freely and the material is porous, fibrous, and thick it should be a good sound absorbent. Porosity provided it is above 70%, does not much affect absorption. Below this figure sound absorbency decreases as porosity decreases. The table in the next pages gives absorbent materials and for building materials and furnishings. Several important conclusions can be drawn from examination of this table.

(a) For absorbent materials, absorption is normally in higher at high frequencies than at low.
(b) Absorption is not always proportional to thickness, but depends on the type of material being used and the method of installation.



Variation of absorption coefficient with thickness of felt absorbent. Note particularly that beyond 1 kHz, all thicknesses give the same α, whereas at low frequencies the absorption is proportional to thickness. Furthermore it requires a very heavy layer to give appreciable absorption at low frequency.

It is clear from this figure that beyond a nominal thickness except at very low frequency, or when installed discontinuousy, as in (c) below.

(c) It is possible to obtain an α greater than 1.0 by using very thick blocks. See "Fiber Blocks" in the table. These are installed at a distance from each other and the edge absorption is very large, particularly at high frequecies.

(d) Installation methods have a pronounced effect.

NOTE:
See Table on coefficients of absroption on chapter IX Air-Borne Noise Reduction

Types of Acoustical Materials

Most commercially available acoustical materials are included in one of the three following catergories:

(1) *Pre-fabricated Units* — These include acoustical tile, which is the principal type of material available for acoustical treatment; mechanically perforated units backed with absorbent material; and certain wall boards, tile boards and absorbent sheets.

(2) *Acoustical Plaster and Sprayed* — On materials, these materials comprise plastic and porous materials applied with a trowel; and fibrous materials, combined with binder agents, which are applied with (sprayed on) an air gun of blower.

(3) *Acoustical Blankets* — Blankets are made up chiefly of mineral or wood wool, glass fibers, kapok batts, and hair felt. The physical characteristics of the materials in each of these catergories will now be considered.

Prefabricated Acoustical Units

Prefabricated acoustical materials have been subclassified in order that similar products may be grouped together. Prefabricated units are separated into three types described in detail below. These groups include tile, absorbent material covered by mechanically perforated units, and certain building boards and sheets.

Perhaps the most *outstanding feature* of an acoustical tile is its "built-in" absorptive value. The tile is a factory-made product; the absorptivity is relatively uniform from tile to tile of the same kind. This makes if foolproof, a highly desirable characteristics. The amount of absorption added to a room by acoustical tile therefore is quite independent of the skill, of the persons who install the material. Another merit possessed by acoustical tile is its relatively high absorptivity. In a factory made product it is possible to control such factors as prorosity (including the number and size of pores), flexibility, density, and the punching of drilling of holes — factor which are paramount in determining the absorptivity of materials, and factors such which often are difficult to control in certain types of acoustical plasters. In addition tile can be given structural and decorative properties which usually are well adapted to the requirements for artistic interiors. Because of its high absorptivity, acoustical tile is well adapted to rooms in which a relatively small surface is available for acoustical treatment.

Several acoustical units like acousti-celotex, fibetetone, cushiontone, and sanacoustic tile, have the advantage that they can be decorated with oil-base paint without having their high absorptivity impaired. This property is due to the mechanically made holes which permit the sound waves to reach the interior of the tile and be absorbed as a result of viscous forces in the tiny pores of the material.

The principal *disadvantages* of an acoustical tile its limitations for architectural treatment and its cost compared with that of other acoustical materials. It is impossible to conceal entirely the points between adjacent tiles, and for this reason such treatments should be limited to rooms or surfaces where a tile or ashlar effect is not objectionable. With types to tile is possible to secure the appearance of a continuous or monolithic surface by using tight unbeveled joints and by decorating an entire surface. But in rooms with low ceilings, or in other rooms with tile of the walls, the ashlar effect is noticeable with any type of decoration. For this reason, the edge is frequently beveled around the tile to emphasize, rather than attempt to conceal, its masonry effect. The bevels also serve to "conceal" slight irregularities in the fitting of the tiles.

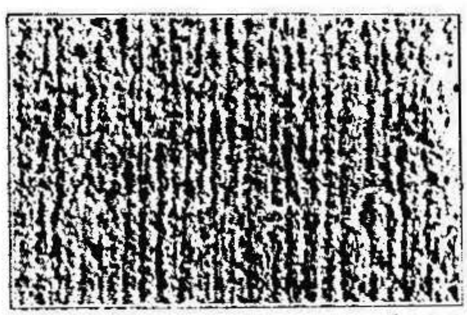
Most types of acoustical tile on the market are relatively costly. In comparing the cost of acoustical tile with that of other types of acoustical treatment it should be borne in mind that the cost per square foot should not be considered alone. Acoustical tiles often are two of three times more absorptive than acoustical plasters, and for this reason as much absorption may be attained with one square foot of tile as with two or three square feet of plaster.

The U.S. Federal specifications SS-A-118 — a classifies prefabricated units into four types. These types and their subclassifications are listed below, together with name of one or more representative commercial products. The figure shows the surface appearance of the different types of materials.

"Type I. Cast Units having a pitted or granular — appearing surface"

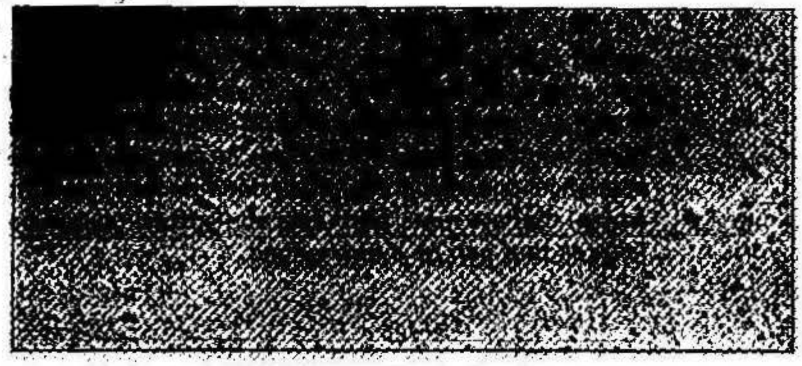
"Class A. All — mineral units composed of small granular of finely divided particles with portland cement bider."

The masonry like surface appearance of the units makes them particularly suited for installation in buildings of the monumental types and in some churches. These tiles are rated as incombustible. Paints normally reduces their sound absorptive properties, but decoration is seldom required. The surfaces of materials in this class are reasonably smooth.



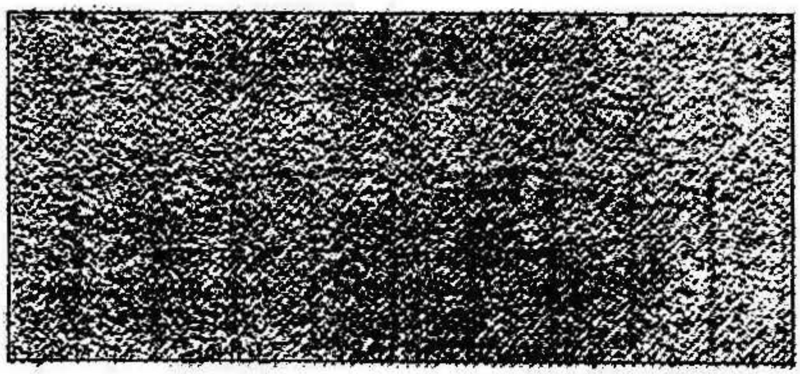
Type I-A (Akoustolith Tile, R. Guastavino Co.)

"Class B. All — mineral units composed of small granules or finely divided particles with lime or gypsum binder."



Type I-B (Muffletone, Standard, Celotex Corp.)

"Class C. Units composed of small granules or finely divided particles of mineral or vegetable origin with incombustible mineral binder.



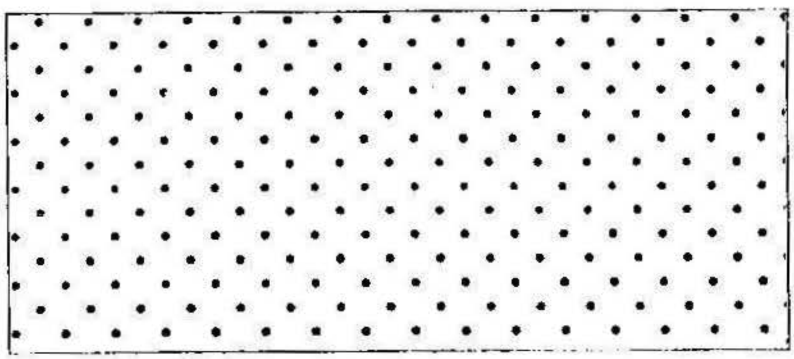
Type I-C (Softone, American Acoustics, Inc.)

"Type II. Units having perforated surface; the perforations to be arranged in a regular pattern."

"Class A. Units having a perforated surface which acts as a covering and support for the sound absorbent material to be strong and durable and substantially rigid."

In this type of unit an absorptive pad, blanket, or rigid element (frequently consisting of compressed mineral wool) is covered by perforated sheet metal or board. The perforated covering does not reduce the absorption to the area covered. For example, the absorption coefficient of a blanket covered with perforated sheet steel which exposes only 15 percent of the absorptive material may have a coefficient, up to 4000 cycles, almost as high as if the covering were not there at all! This is due to diffraction, which is discussed in chapter 4.

Type II — A fabricated units can be painted repeatedly without impairing their absorption, if reasonable care is taken not to fill or bridge the holes with paint. If the holes are 1/8 inch diameter or longer, it is highly improbable that they will ever become bridged by painting. Since the perforated coverings offer good mechanical protection for the absorptive material, the units can be installed in locations where they will be subject to considerable wear and tear. Most units of this class are incombustible. Many are moisture-resistant and hence find application in swimming pools, kitchens, etc. Some offer interesting possibilities for combining acoustical construction with air conditioning and lighting control. For example, ther are metal pan units and special flush-type fluorecent lighting fictures that can be interchanged.



Type II-A (Arrestone, Armstrong Cork Co.)

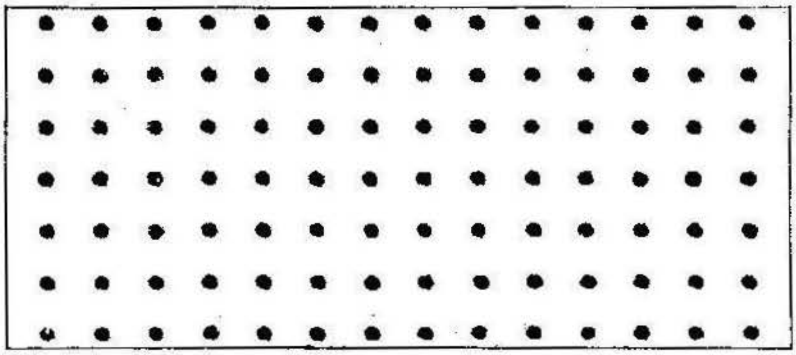
Other brands

ACOUSTEEL	CELOTEX CORP.
ACOUSTIMETAL	NATIONAL GYPSUM CO.
ARPHON	A.B. ARKI (Sweden)
PERFATONE	UNITED STATES GYPSUM CO.
SANACOSTIC UNIT	JOHNS — MANVILLE
TRANSITE ACOUSTICAL UNIT	JOHNS — MANVILLE

"Class B. Units having circular perforations extending into the sound absorbent material."

Prefabricated units of this class usually have large perforations and therefore are especially serviceable in installations that require frequent redecoration. Laboratory and field tests show that these tiles may be painted repeatedly without noticeable reduction of their sound-absorptive properties.

The presence of holes in porous materials, as in acousticelotex or cushiontone has the effect of greatly increasingly the absorptivity of the material. The holes increase both the superficial area and the effective porosity of the material. The perforations can be used to conceal the heads of nails or screws when used for attaching the units to wood furring strips or wood decking.



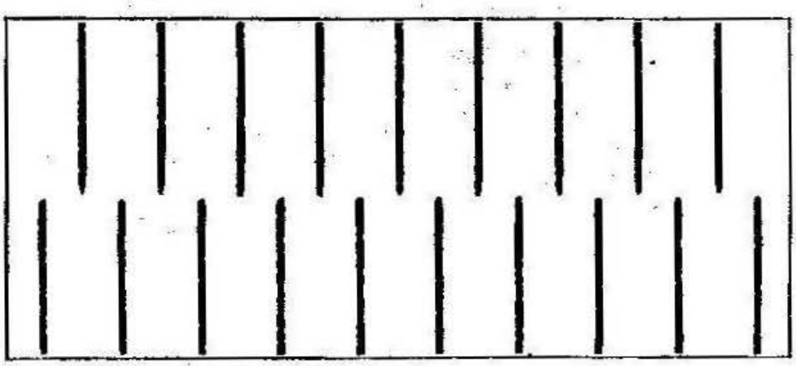
Type II-B (Acousti-Celotex Cone Tile, Celotex Corp.)

Other brands:

ACOUSTI-CELOTEX MINERAL TILE	Celotex Corp.
ACOUSTIFIBRE	National Gypsum Co.
CUSHIONTONE	Armstrong Cork Co.
FIBERTONE	Johns — Manville
PAXTILES	Newalls — Insulation Co., Ltd. (England)
STENITPLATTA	A.B. Arki (Sweden)

"Class C. Units having slots or grooves extending into the sound absorbent material."

The action of the slots or grooves is similar to that of the holes in the tiles of the preceding classification.



Type II-C (Auditone, U. S. Gypsum Co.)

Other brand:

TREETEX (Type C)	Treetex, Ltd. (Sweden & England)

"TYPE III Units having a fissured surface."

This type, includes tiles differing widely in composition. Some consist largely of filaments or mineral wool granules; in others, vermiculite or cork is the principal ingredient. The action of the fissures in causing absorption of sound by the units is very similar to that of the perforations in type II — B. These tiles have surfaces that are sanded or planed smooth. The may be painted without loss of absorption if the fissures are numerous and are not filled with paint.

Type III (Corkoustic, Armstrong Cork Co.)

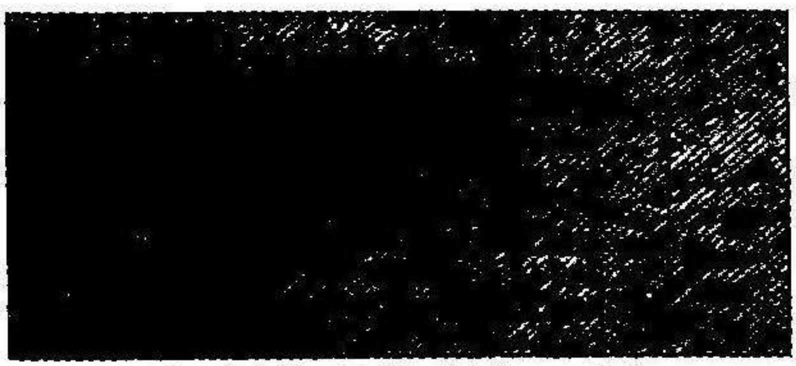
Other brands:

ACOUSTONE	United States Gypsum Co.
FISSURETONE	Celotex Corp.
TRAVERTONE	Armstrong Cork Co.

"TYPE IV Units having a felted fiber surface."

"Class A. Units composed of long wood fibers."

Units of this class are made of wood shavings of excelsior, generally pressed together with a mineral binder. The wood fibers may be fine, medium or coarse.



Type IV-A (Absorb-A-Noise, Luse-Stevenson Co.)

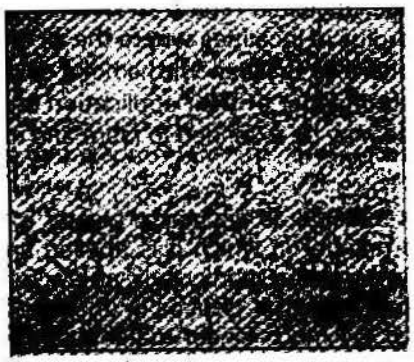
Other brands:

ABSORB-A-TONE	Luse — stevenson Co.
L.W. INSULATION BOARD	Brown and Tawse, Ltd. (England)
POREX	Porete Manufacturing Co.
SONO-FHERM	Sono — Therm Co.

"Class B. Units composed of fine felted vegetable fiber or wood pulp."

Included in this class are small tiles and also acoustical fiberboards. In general, these materials are not fireproof. The fiberboards provide a means of obtaining absorption at relatively low cost. They are commenly manufactured in large panels, K feet wide, and 8, 10, or 12 feet long. The use of fiberboards presents a difficulty in the matter of decoration and redecoration. Oil, lead, and other non-porous paints will close the surface pores of the materials and hence, destroy the absorptive valve.

On the other hand, thin dyes and stains, stencil designs with heavier paint dusted on with a pounce-bag can be used without impairing the acoustical valve of the material. In spite of these limitations, certain acoustical fiberboards are useful for the control of noise and reverberation in buildings. There are many school and industrial jobs, where cost is an important consideration, in which fiberboards may be used to advantage.

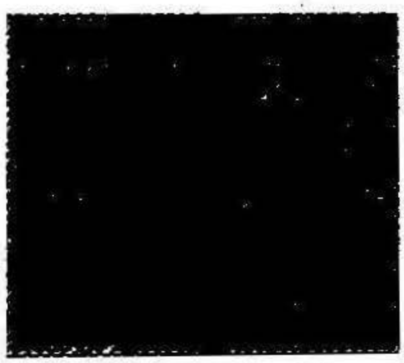


Type IV-B (Econacoustic, National Gypsum Co.)

Other brands:

ACOUSTILITE	Insulite Co.
FIBRACOUSTIC	Johns — Manville
LLOYD BOARD	Lloyd boards, Ltd. (England)
NUWOOD BEVEL LAP TILE	Wood Conversion Co.

"Class C. Units composed of mineral fibers."



Type IV-C (Q-T Ductliner, Celotex Corp.)

Type IV — C (Q-T Ductliner, Celotex, Corp.)

Other brands:

AIRACOUSTIC SHEETS	Johns — Manville
FIBERGLASS ACOUSTICAL TILE	Owens — Corning fiberglass
PAXFELT	Newalls Insulation Co., Ltd. (England

Acoustical Plaster and Sprayed — on Materials

The use of selected types of acoustical plastic materials has proved highly satisfactory for the treatment of offices, school rooms, corridors, and many public building. They can be used in most places where ordinary lime or gypsum plaster can be used without altering the architectural effects. Two coats of acoustical plaster may be aplied instead of the finish coat in the ordinary plaster treatment for an added little cost per square meter. These meterials have dificiencies in regard to cleaning and decorating. Although these shortcomings are not seroius in localities where the air is relatively clean, They are an important consideration where air is laden with smoke or dust. As plastic materials are improved and as the correct manner of their application is more fully understood and practiced by plasters, their use may be extended to more and more buildings.

The absorptivity of such material as acoustical plaster is dependent on its thickness and composition and on the manner in which it is applied and dried. As the thickness is increased, the absorptivity increases, particularly at low frequencies. However, for plasters of the type applied with a trowel, it is usually uneconomical to increase the thickness beyond 1/2 inch (.025). If too much binder material is used, the plaster is not sufficiently porous. If an insufficient amount of binder is used, the plaster does not set hard and its tensile strength may be less than that required for adequate structural bond; under such circumstances, it may dust or pop off the wall. Likewise, if the undercoats of plaster are too wet (green), the binder material forms an impenetrable film at the surface; whereas, if the undercoats are too dry, the binder material is absorbed by the undercoats and the plaster will crumble. Since the absorption coefficients of acoustical plasters are dependent on such factors as the suction behind the plaster, the pressure applied to the trowel, and the manner of floating, texturing, or stippling, the journeyman should be instructed to exercise great care in applying and finishing these materials. A large measure of the success or failure which attends the application of acoustical plaster depends on the drying out of the plaster. The surface to which it is applied accordingly it is advisable to prepare scratch and brown coats which will draw the water from the acoustical plaster and thus prevent the formation of a non-porous film on the finished surface. It is also advisable to provide good drying conditions for the plaster and to float or drag the surface or the plaster just before it takes its initial set. Unless these initial precautions are observed, the use of acoustical plaster may prove dissappointing on the other hand, if these precautions are carefully followed, a good brand of acoustical plaster will be found to be well adapted to many types of buildings where large surface areas are available for treatment, and where very high absorption coefficients are not needed, In large buildings, it is advisable to require the contractor to plaster a small room for test and approval before the material is applied to other parts of the building by competent journeymen.

In selecting an acoustical plastic material it is desirable to consider its adhesive and cohesive properties, its resistance to fire and abrasion, its ease of application, its texture, and its maintenance (such as cleaning and decorating) as well as its coefficients of sound absorption. If it becomes necessary to use plastic material which will not withstand the wear and abrasion to which the walls near the floor will be subjected, it is a good plan to provide a wainscot of harder material, such as wood or hard plaster. The wainscot should extend up to a height of about 6 or 7 feet above the floor.

Acoustical materials for plastic application are classified into three groups in U.S. Federal specification SS - A - 118 - a.

"TYPE I. ACOUSTIC PLASTER"

This shall be composed of a cementitious material such as gypsum, portland cement, or lime with or without an aggregate.

Brands:

ATOZ, KALITE, SABINITE, SOFTONE
ZONOLITE, PLASTACOUSTIC

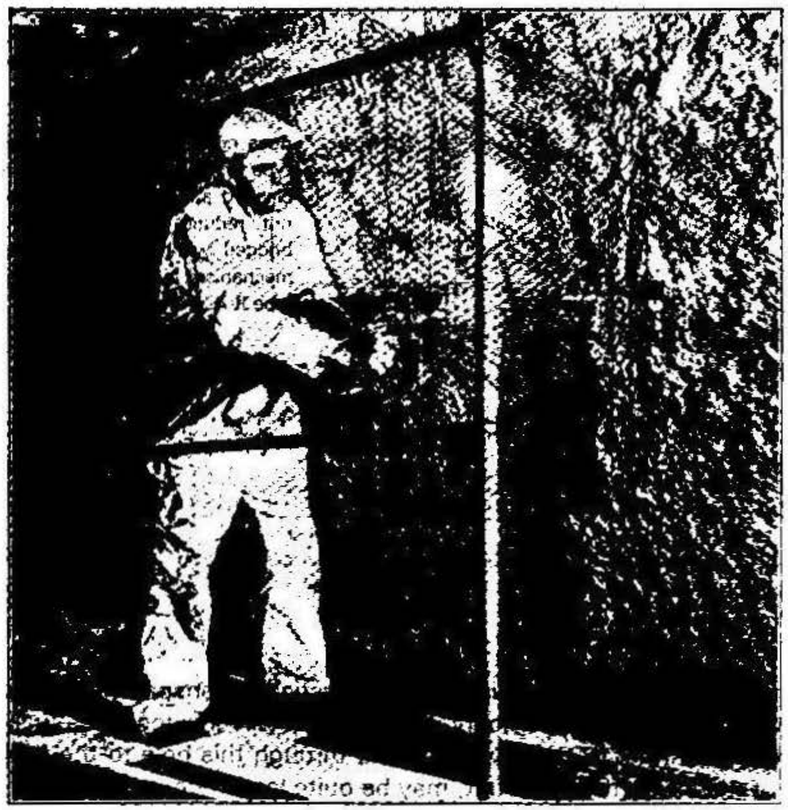
"Type II. Acoustic materials other than acoustic plaster which are applied with a trowel."

Brand: ACOUSTIPULP

"Type III. Fibrous materials combined with a binder agent and which are applied by being sprayed on with an air gun or blower."

Brands:

LIMPET, SPRAY-ACOUSTIC



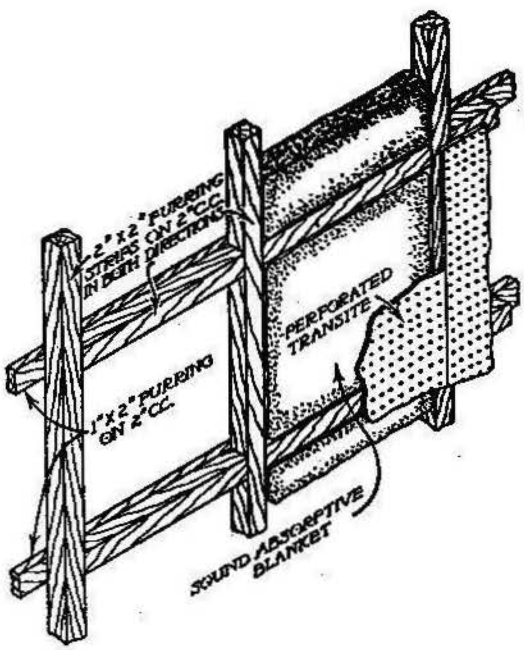
Acoustical Blankets

The material used most commonly in the fabrication of acoustical blankets are mineral wood, hair felt, wood fiber, and glass fiber. Although, the thickness of these blankets is generally between 1/2 and 4 inches, blankets of greater thickness are sometimes used in special applications. These matetials are more absorptive in the low — frequency range, principally because of their greater thickness, than are most other types. Hence, blankets sometimes are useful for controlling the acoustical characteristics of studios and auditoriums that require "Balanced absoprtion. Including a considerable amount at low frequencies."

The absorption coefficient of a blanket mounted against a wall depends on its density and thickness and on the frequency of the incident sound. Increasing the thickness of the blanket increases its absorptivity, principally at low frequencies, slightly at the "highs". The effect of an air space behind a blanket is, in general, to increase its absorption at low frequencies.

The fibers in certain types of blanket, especially some mineral -- wool products, have a tendency to "settle, often as a result of building vibration; "settling" alters the acoustical characteristics of the blanket. For this reason, blankets fabricated of materials that tend to settle are frequently quilted at intervals of a few inches. In other cases, the material are given additional structural strenght by the addition of a binder material, or by a wire — mesh screen or hardware cloth on one or both sides of the blanket.

Perforated Facings

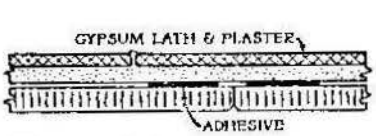


A perforated facing such as plywood, metal, or fiberboard constitutes a very practical covering for an acoustical blanket. The figure shows how a perforated lawanit board can be used for this purpose. Except for the small holes, the appearance of the plywood covering the patches of absorptive material does not differ from other portions of the wall. This type of facing has the advantage that it can be easily cleaned and decorated, and repeatedly painting does not reduce its absorptivity if the holes are not bridged with paint. In this respect and also in the mechanism by which it absorbs sound, it is similar to type II-A prefabricated units.

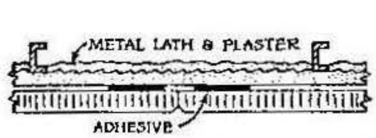
Owing to diffraction, the facings are "acoustically transparent" over a wide range of frequencies. Thus, if a plane sound wave is normally incident on a wall containing a small aperture, the ratio of the flow of sound through this hole to the flow through an equal area of the incident wave front, may be quite large — even in excess of 10. This ratio is largest at low frequencies, and smallest at high frequencies where the diffraction effects are neglible. Therefore, the coefficients of blankets covered with perforated facings in which only 5 to 10 percent of the surface area is perforated are affected relatively little at low frequencies but decrease at the highs. For most applications, 3/8 inch centers, will be found to be satisfactory. By spacing the holes farther apart, the absorption at high frequencies can be further diminished without appreciable loss of absorption at the low frequencies. If muslin or similar fabric is used to cover the blanket, it should be very porous. Any form of decoration or flamefroofing should not clog the pores of the covering. Such a covering does not alter appreciably the absorption of the blanket. The combination of a perforated panel like 1/8 — inch plywood with an air space and a blanket of rock wood or glass fiber provides a type of acoustical treatment that can be highly absorptive at low frequencies and progressively less absorptive at higher frequencies.

Mounting Acoustical Materials

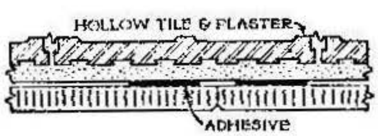
The manner of mounting acoustical materials can influence markedly their absorptive properties. Certain materials that are unsatisfactory when applied directly against a rigid wall may be satisfactory when they are mounted some other way; for example, with an air space behind them. The effect is an increase in the absorption at low frequencies, due partly to the flexural vibration of panels of two material. Within certain limits, increasing the spacing from the wall increases the average absorption and alters the frequency at which maximum absorption occurs — the lowest resonant frequency of the panel. Since the size of a panel is a factor that determines this resonant frequency, the frequency region in which increased absorption takes place, owing to flexural vibration, depends on the separation between furring strips. For furred-out fiber-board or plaster on lath, the separation between strips is frequently determined by the mechanical properties of the material; and for prefabricated units the spacing is generally determined by the size and physical properties of the units. In other applications, 16 inches on centers is usually satisfactory. In music rooms, and in radio or sound-recording studios, random spacing of the furring strips may be used to distribute the resonant frequencies and thus provide a more uniform absorption throughout a wide range of frequencies.



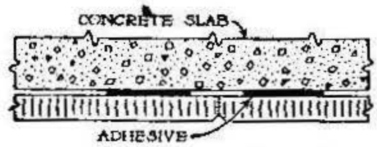
Tile cemented (by means of adhesives) to plaster on gypsum lath.



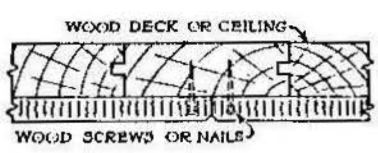
Tile cemented direct to a metal lath and plaster surface.



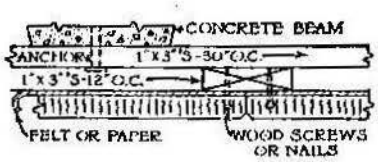
Plaster on hollow tile is an ideal surface for application of sound-absorptive tile by adhesives.



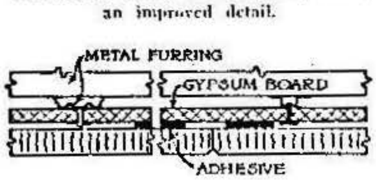
Tile applied on concrete ceiling surfaces with a heavy-bodied adhesive.



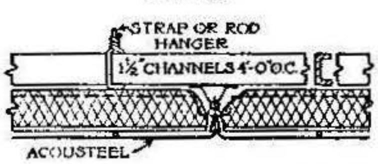
Application of tile to timber or plank construction (with wood screws) offers an improved detail.



Application of tile to wood furring. Use of wood screws provides improved anchorage.



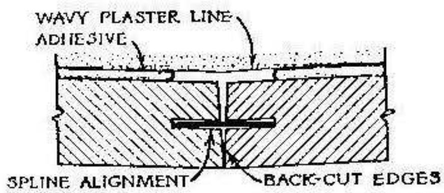
Acoustical tile cemented to a suspended gypsum board ceiling. This method has the advantage of light weight.

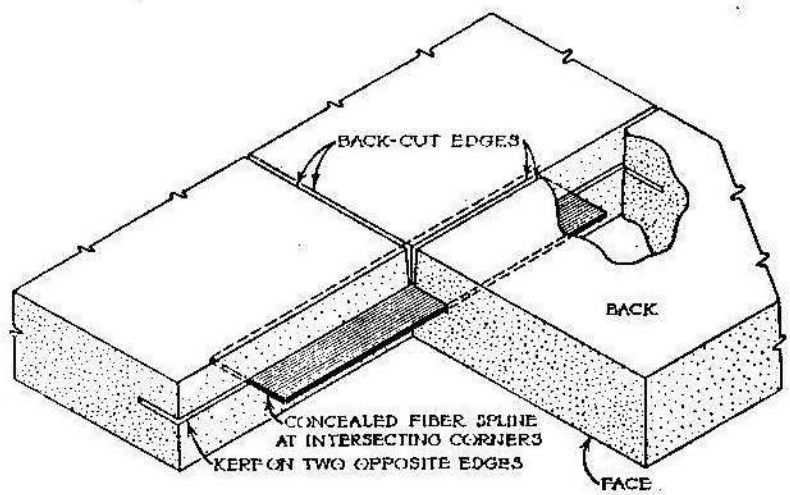


Acousteel installed as a suspended ceiling. The T-bars may be applied to other suitable surfaces.

Acoustical tiles are most frequently mounted by adhesives, nails or screws, or by a mechanical system such as "T-splines" which engage in a horizontal kerf along the side edges of the tiles. These types of mountings are illustrated in the figures

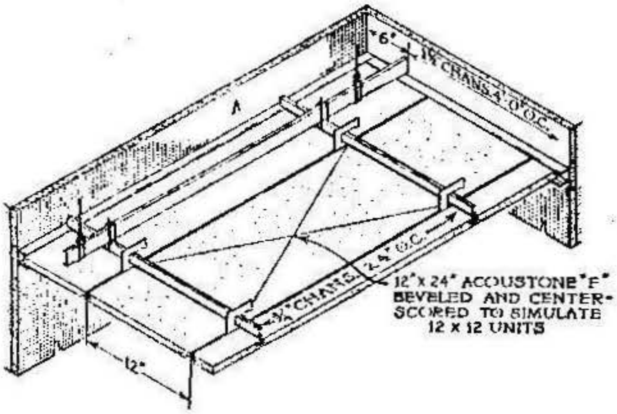
In many instances a combination of two methods is used. No one type of mounting will depend on the physical properties of the acoustical material, the base to which it will be applied, the time required for installation, and labor costs. However, other factors are frequently the controlling ones. Thus, the adhesive method of mounting is particularly advantageous on a job. Where noise must be kept to a minimum during installation, as in a hospital. The adhesive method is also quick, economical, and clean. The adhesive should be bonded to both the material and the wall or ceiling. Since the failure to secure a good bond may result in the tile becoming loose, adhesive applications should be made only by individuals thoroughly skilled in the art. In general, tiles larger than 12 inches by 24 inches should not be applied with adhesives alone. Nails or screw may be necessary; they support the unit while the adhesive sets, thereby securing a stronger mechanical bond and offering a double protection against loosening.

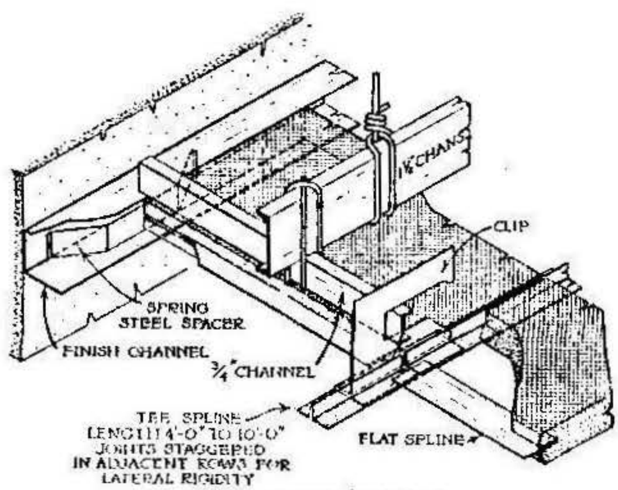




Tiles fastened by screws are usually held more securely than those fastened by nails. Also, they can be removed quickly. Facilities are now available for rapid application by electrically driven screws. Either nails or screws can be used to mount acoustical materials on wood furring strips. By this means a new ceiling can be furred down to any desired level,thereby concealing pipes, conduits, air-conditioning ducts, etc. The wood furring method of mounting also permits the tiles to vibrate flexurally; this vibration gives increased absorption in the low-frequency range. Where the acoustical units are subject to breakage, as they may be in a gymnasium, a stiff backing for the tiles should be provided. Gypsum board provides such a backing; it also is fire-resistant. It can be used to level off an existing irregular ceiling, or as economical substitute for a conventional lath and plaster backing in new construction.

A number of manufacturing of acoustical materials have mechanical systems for the installation of prefabricated tiles which enable units to be removed relatively easily and replaced after the original installation has been made. Mechanical systems provide a convenient means of furring below ceiling obstructions with incombustible supporting members, as shown in the figure below.





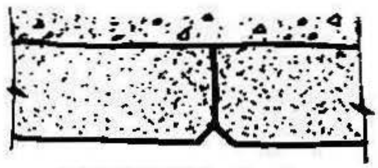
DETAIL AT WALL A

Most acoustical materials are efficient thermal insulators. For this reason, care should be taken to prevent condensation on the underside of the slabs or decks on which the materials is installed. An undersirable dislocation may result from air flow through the cracks between tiles or even through very porous tiles. This flow of air, called breathing, occurs most often in air-conditioned rooms. It can be minimized in installation by the application of a layer of building paper directly behind the tiles. This precaution may be advisable in some wood furring installations.

Although some acoustical materials, such as mineral tiles, are not affected by changes in humidity or moisture in a room, others — those made of cellulose products, such as wood or vegetable fibers — tend to expand upon absorption of water vapor and to contract upon drying. This possibility must be borne in mind when hygroscopic acoustical materials are being installed. The tiles should become adjusted to the moisture content of the room in which they are to be installed. Then, if the humidity is high, the individual units be butted up against each other tightly, so that when dry conditions prevail noticeable gaps, will not appear. On the other hand, if the tiles are installed in a very dry atmosphere, they should be fitted with a slight gap, about 1/64 or 1/32 inch. (0.8 mm to

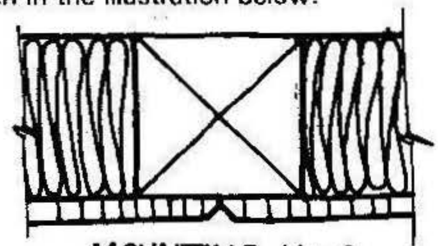
1 mm). (such gaps will not be noticeable if the tiles have beveled edges.) If this precaution is not taken, the tiles, by expanding, may warp or may exert enough force on one another to become loosened and thus become unsightly or even unsafe.

Some common standardized mounting are given in the illustration below.



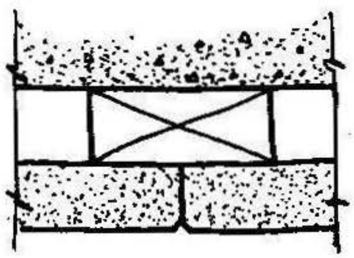
MOUNTING No.4

RIGIDITY FASTENED TO CONCRETE



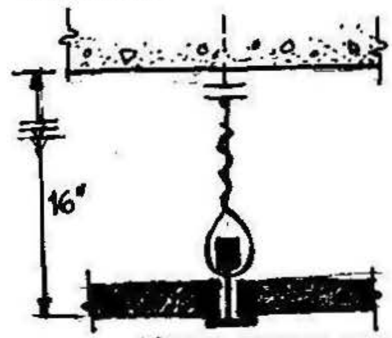
MOUNTING No.8

MINERAL WOOL BETWEEN FURRING PERFORATED FACING FASTENED TO FURRING



MOUNTING No.2

NAILED TO 1X3 WOOD FURRING 12" OC



MOUNTING No.7

STANDARD HUNG CEILING CONSTRUCTION

Absorption by Patches of Materials

The location and distribution of absorptive material in rooms affects (1) the absorption due to the material and (2) the distribution of sound in the room. For example, twenty five small areas — "Patches" — of material, each 1.20 square, will absorb more sound than will one large patch having an area of 100 sq. ft. (9 to sq. m.) This dependence of absorption on the size of patch is frequently referred to as the "area effect". Although the application of absorptive material in the form of small patches or narrow strips is more effecient than a uniform treatment, it is usually not the cheaper method of obtaining a specified amount of absorption with a given material since the cost of installation of patches on a per square meter basis is generally much higher than is the cost for uniform coverage.

The absorption by a patch of material is not independent of its position on the walls of a room. The most effective positions for the usual types of absorptive materials, are not at (or close to) the corners, especially at frequencies at which the wavelengths are large compared with the dimensions of the patch. The next most efficient positions are along the edges between two walls. It has been shown that the distribution of sound pressure in a room is a function of the distribution of the absorptive materials on the walls. Owing to the effects of diffraction. The application of acoustical material in patches, distributed more or less at random on the walls, provides a more diffuse sound field in the room than would be obtained by uniform treatment of the walls. A certain amount of diffusion is generally considered to be a requirement for good acoustics.

Special Sound-Absorptive Construction

Many absorptive materials and constructions that are not described earlier above are useful or even indespensable for certain types of acoustical installations. Often these special treatments, when used with understanding and imagination, provide not only better acoustics that can be obtained by the use of the standards or "classified" materials, but also a more artistic appearance, sometimes at a considerable reduction in cost.

Panel Absorbers

Thin panels, if made sufficiently durable and flexible materials like pressed wood fiber or paper boards, plywood, or plastic boards, can be employed for ceilings, wainscoting, or even for the entire walls of rooms where low-frequencies absorption is required. Such materials, if used for walls or ceilings of small rooms, such as music studios, classrooms, and offices, reduce the amount of additional absorption required for optimum.

The effective stiffness of a thin panel is influenced by the presence of an enclosed air space back of it, and therefore the air space affects the absorption characteristics of the panel. A 1½" air space in a 1/8" x 4' x 8' plywood will give an absorption coefficient of 0.25 of 205 frequency in cyles per sound. Increasing the air space to 2¼" air space, it becomes 0.4 on a205 frequency. The resonant frequencies are altered and the absorption is increased as a result of increasing the depth of the air space.

The absorption coefficient of a thin wood panel can be increased by placing an absorptive material, such as mineral —wool blanket, in an enclosed air space behind the panel, or by spot — cemeting the absorptive material directly to the panel.

Draperies

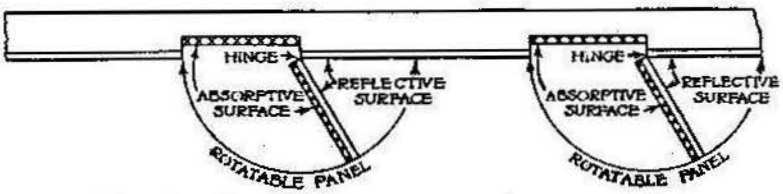
In general, draperies are not satisfactory for the absorptive treatment of an auditorium. Although very absorptive at high frequencies, they are only slightly absorptive at low frequencies. An auditorium so treated may sound "boomy". Hence, the use of draperies, unless especially designed, should be restricted to places such as doorways or prosceniums. For maximum absorption, they should be made of heavy, lined and interlined velours (or equivalent material) and should have a gather of 100 to 200 percent. In order to increase their absorption at the lower frequencies, hangings used to cover highly reflective surfaces should be hung at least 6 inches to 1 foot from the wall and should be gathered into deep folds. Movable draperies provide a convenient means of altering the total absorption in a room.

Variable Absorbers

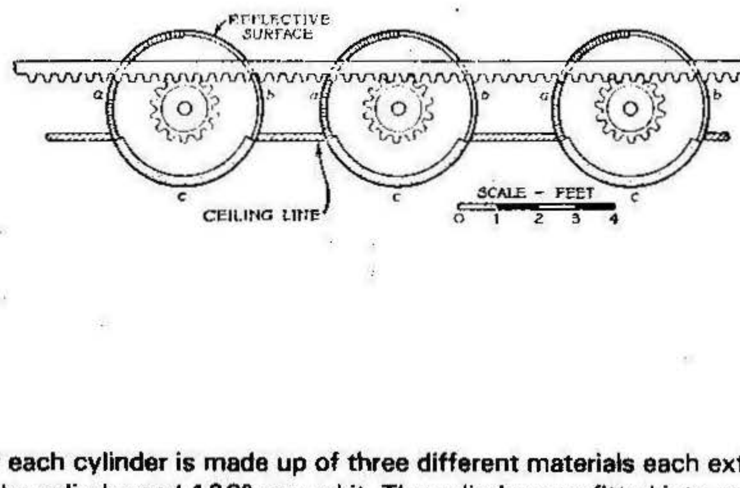
Certain rooms, especially some broadcast studios and music rooms make use of variable absorbers such as hinged panels, rotatable cylinders or movable draperies. The hinged panels generally are absorptive on one side and reflective on the other; the cylinders in-

corporate various combinations of absorbers and reflectors. These special devices are utilized for varying and controlling the acoustical conditions in the room. In general, the control of the following three factors is desirable: (1) the magnitude of the average absorption over the greater part of the audible frequency range (2) the shape of the absorption is frequency characteristic, and (3) the scattering or dispersion of sound in the room. Scattering influences, the uniformity of the sound-pressure distribution within the room.

A variable absorptive treatment should provide the possibility of varying the total absorption in the room over a wide range — in some instances by a ratio of at least 3 to 1. If hinged or rotatable panels are used which have an absorptive surface one side and a thin reflective surface on the other, care must be exercised so that the reflective surface, such as plywood facing, does not act as resonant panel backled by an absorptive material. If this precaution is not taken, total variation in the absorption may not be so great as expected or desired.



Hinged-panel arrangement for changing the absorptive characteristics of a room.



Rotatable Cylinders

The convex surface of each cylinder is made up of three different materials each extending the full length of the cylinder and 120° around it. The cylinders are fitted into openings of such size that 120° of each projects through a suspended plaster ceiling.

Material (a) is a 2 inch layer of fiberglass, having a density of 6 pounds per cubic foot, covered with ¼ inch perforated plywood (There are 1024 circular holes are 1/8 inch in diameter and are arranged 3/8" on centers, Material (a) is moderately absorptive at low freguencies and is increasingly absorptive at higher frequencies;

Material (b) is 1/8" unperforated plywood backed with a 2 inch layer of fiberglass. It is most absorptive at low frequencies and is decreasingly absorptive at higher frequencies.

Material (c) is ½ inch unperforated plywood. It is slightly (but uniformly) absorptive at all frequencies.

Rotatable Panels

This changes the total absorption of a room they differ from the cylinders in that their rotation generally changes the shape of the walls or ceiling. Hence, the rotation of panels has a pronounced influence on the diffusion as well as on the absorption of sound in the room. One side of the panel is flat and is covered with acoustical tile; the other side of the panel is convex and is "treated hardboard". This panels control diffusion. They can be bucked by an air space and an absorptive blanket. This can be controlled by push button.

Suspended Absorbers

In certain types of enclosed spaces (for example, in large machine shops having extremely high ceilings) it is difficult to apply the conventional type of acoustical treatment so that absorptive surfaces will be located near the source of noise. In such cases, recourse may be had to relativity small prefabricated units of absorptive material hung from the ceiling. The use of such suspended absorbers is especially adaptable to locations where there are no extended surfaces on which to apply acoustical tile, or similar materials, and where it would be difficult or expensive to install a false ceiling because of pipes or other obstructions. Such treatment need not interfere with existing lighting or ventilating systems. Owing to diffraction, the effective absorption per unit area or per unit weight of small absorbers can be very high. Sound waves impinge on both sides of the absorbers, thus enchancing their absorption.

6

ACOUSTICAL DESIGN OF ROOMS

PLANNING FOR GOOD ACOUSTICS

Planning for good acoustics in a building begins with the selection of the building site and continues through all stages of designing. The architect will avoid inexcusable errors in design if he sets up a check, list of the necessary and sufficient measures to be taken for obtaining good acoustics. These steps, approximately in chronological order as follows:

(1) The selection of the site in the quietest surroundings consistent with other requirements.
(2) The making of a noise survey to determine how much sound insulation must be incorporated in a building to meet specified requirements of quietness.
(3) The arrangement of the rooms within the building.
(4) The selection of the proper sound-insulation construction.
(5) The control of the noise within the building, including solid-borne as well as air-borne noise.
(6) The design of the size of each room that will insure the most advantageous flow of properly diffused sound to all auditors, and that will enhance the aesthetic qualities of speech and music.
(7) The selection and distribution of the absorptive and reflective materials and constructions that will provide the optimum conditions for the growth, the decay, and the steady-mate distribution of sound in each room.
(8) The supervision of the installation of acoustical plaster, plastic absorbents, or other materials whose absorptivity is dependent on the manner of application.
(9) The installation of sound-amplification equipment under the supervision of a competent engineer; wherever such equipment is necessary.
(10) The inspection of the finished building including tests to determine whether the required sound insulation, sound absorption, and the other acoustical properties have been satisfactorily attained.
(11) Maintenance instructions, in writing, to be left with the building manager, indicating (a) how the acoustical materials can be cleaned or redecorated (b) which finishings in the building must be retained to maintain good acoustics, (c) how, in large speech and music rooms where high-quality reproduction is desired, the humidity should be maintained in order to avoid excessive absorption of high-pithed sounds, and (d) how the sound amplification system should be maintained.

Requirements for Good Acoustics

In the design for rooms intended for speaking purposes the prime objective is the realization of conditions that will provide good *intelligibility of speech*. This phrase, as used by telephone engineers, signifies how well speech is recognized and understood. In the design of music rooms the prime objective is the most favorable enrichment of the total quality and tonal blending of the sounds. It is necessary to provide not only the opimum conditions for listening to music but also the possible conditions for the rendition of music by skilled artists. When a radio, violin, or any musical instrument is played in an enclosure, the enclosure is, in effect, a part of the instrument; that is, the instrument is *coupled* to the room, and the instrument excites the resonant frequencies of the room. A high-quality radio or a world-famous stradivarius cannot produce high-quality music in a room that has poor acoustics.

The above check list is a practical aid to the fulfillment of the requisites for good acoustics. These requirements, which are applicable to all rooms used for speech and music, may be stated as follows:

(1) All noises, whether of outside or inside origin, should be reduced to levels that will not interfere with the hearing of speech or music.

(2) The room's shape and size should be designed to (a) give proper diffusion to the sound (b) reinforce the sound reaching the audience, especially toward the rear seating area, and (c) contribute to the attainment of a favorable ratio of direct to reflected sound for all auditors. Although these desirable conditions are also affected by the distribution of the absorptive materials and by the sound — amplification system by the shape and size of the room, it is often necessary to design special wall and ceiling surfaces to act as reflectors for the reinforcement of sound at the rear of the room, and it is sometimes essential to introduce splays or other surface irregularities to provide proper diffusion of sound.

(3) The reverberation time vs frequency curve should approach the optimum characteristics, which are determined by the volume and type of room. The fluctuations in the growth and delay curves should be such as to yield optimum reverberation conditions.

(4) Provision should be made for reinforcing the speech and music in a room so that sound level will be adequate in all parts of the room. In a small room, this requirement can be met by the proper design or reflective surfaces (walls, floors and ceilings); in a large room, in addition to the proper design of the reflective surfaces, a high-quality sound — amplification system is indespensable.

In general, the above four requirements are necessary and sufficient for providing satisfactory acoustics in all rooms. In view of the differences between speech and music, the requirements stated above are not identical for speech rooms and for music rooms. There are, however, certain broad features that apply to both: Freedom from disturbing noise, proper shape (a room shape that is good for music usually will be satisfactory also for speech) and a sufficient sound level for all auditors.

For the average listener, a sound level of about 65 db is adequate for good intelligibility of speech in reasonably quiet surroundings (noise levels of about 40 db), and this level is the optimum average level based on listener preference for both speech and music. In all good music rooms, as in all other rooms in which listening is a required function, the noise level should be low — at least 2 or 3 db lower than the unavoidable noise level of an attentive audience during the silent pauses in music. The noise level of an attentive audience is of course a variable quantity, depending on the size, age, and other aspects of the individuals, but the average level is about 40 db. The noise level in the room when no audience is present should not exceed about 35 db.

In a room the distribution of sound radiated by a source is greatly affected by the boundaries of the room. The distribution is altered; the sound levels are generally raised; and other phenomena such as room resonance, reverberation, and diffusion are introduced. The room can be so designed that its effect on the distribution of sound throughout the room can be very advantageous for good listening.

Individuals in a large ensemble, like a chorus or orchestra are dependent on useful reflections to hear each other adequately. This is an indespensable requirement. Consider a large orchestra seated on a stage. A player in the se-

cond — violin section may be 50 feet about 16 m. from some of the woodwinds. If this orchestra is in the open air without benefit of an orchestra shell or other reflective surfaces, the second-violin player may hear the near-by violins at a sound level 20 db. higher than that of the woodwinds, which are ten times as far away. much of the time, under such conditions, he will not hear the woodwinds at all and may get "out-of-step" with them. *The separate players must hear each other if they are to play in perfect synchronism.*

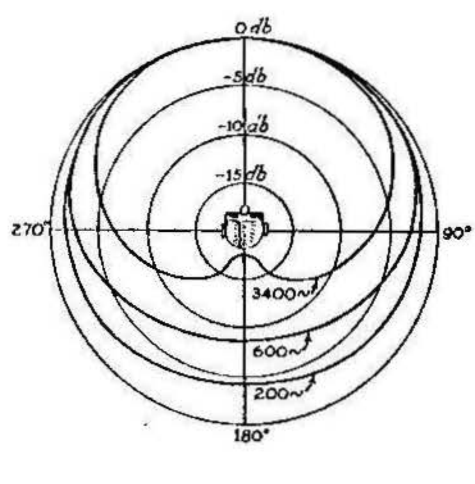
Speech ordinarily requires somewhat less reverberation than music, and it is chiefly in this respect that acoustical properties of music and speech rooms differ. In order to provide the best possible acoustical environment, a music room must also have optimum reverberation characteristics for both performers and listeners. In general, the part of a room (stage platform, or one end of the room) occupied by the performers should have surroundings that are somewhat more reflective than the part occupied by the audience.

Design of Room Shape

Good acoustical planning is based upon many significant factors that affect the insulation, generation, transmission, absorption, reflection, diffusion and hearing of sound. Each element is important; the neglect of any one may mar or ruin an otherwise good design.

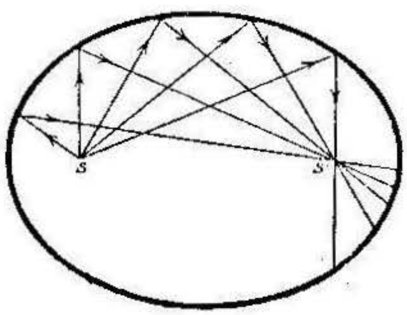
The shape of a room is one of the important factors affecting its acoustical properties. Hence, the determination of the most desirable shape is a problem that the architect should know now to solve.

1. FLOOR PLAN
The design of an auditorium or a lecture room usually begins with the layout of the floor plan. The seating should be arranged so that the audience is as near the stage as is consistent with the requirements set by the distribution of sound from the source and with those for good visibility. Thus, although an audience can be brought nearer the speaker in a room having a square floor plan than in one in which the greater than the width, the latter is preferable. One of the reasons for this preference can be visualized easily by referring to this figure; which shows how sound is distributed around the head of a person who is speaking.



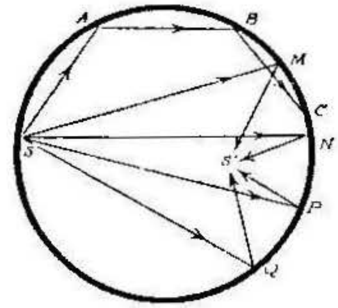
The sound level, especially in the higher frequency range which is responsible for a large percentage of the intelligibility drops off rapidly at right angles to the direction the speaker faces. Hence, the front seats along the sides are not very satisfactory for hearing of speech in a large, square room and these seats are usually out of the "beam" of the loudspeakers as normally used in sound – amplification systems. In a small room the sound level is sufficiently high for good hearing for a wide range of the ratio of length to width. It is apparent, then, that the optimum ratio of length to width for a room is not a fixed number, but varies with size and shape of the seating area; it also depends on whether a sound – amplification system is used. For most rooms, ratios of length to width of between 2:1 and 1:2:1 have been found satisfactory.

Circular and elliptically shaped floor plans nearly always give rise to focusing effects, non-uniform distribution of sound, and echoes. Two prominent defects are illustrated in the two figures (a) and (b) below. In the circular plan fig. b sound originating at s and directed at nearly grazing incidence to the walls, as in the direction SA, tends to creep along the side of the wall. Sound reflected from the rear portion of the cylindrical walls, as rays SM, SN, SP, and SQ, are brought to a focus at approximately S'. This focusing defect is even more pronounced in the elliptical plan on fig. (a) especially when the source is at "S".

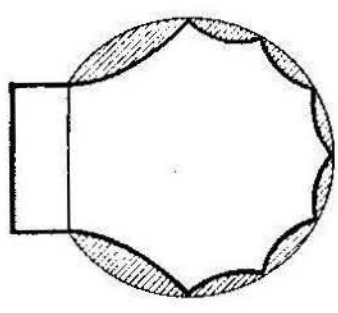


(a)

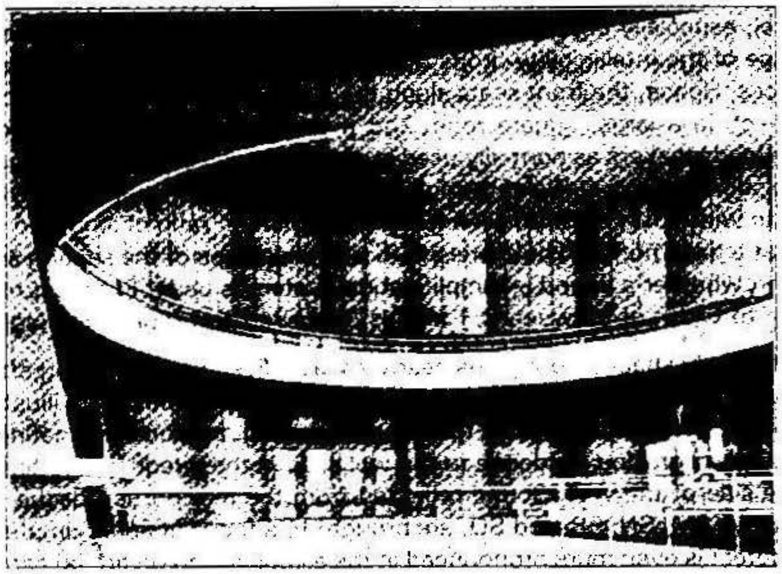
(b)



One focus, as indicated. Here, the concentration of reflected rays in a small region could be partially overcome if the source were moved from a focus; nevertheless, the distribution of sound would remain very non-uniform. In both elliptical and circular plans, the acoustical conditions can be greatly improved by the addition of cylindrical diffusing surfaces, as in fig (c). fig. (d) is a room having such wall surfaces.



(c)



(d)

In order to bring a large audience as close as possible to the stage of an auditorium, it is advantageous to design a floor plan with diverging side walls. Reflections from these walls can aid in the establishments of a higher sound level at the rear of the auditorium, but these reflections must be carefully controlled. Path — length differences of 65 feet or more between direct and reflected sound give rise to echoes. Path — length differences from about 50 to 65 feet produce a blurring quality which may result in a lack of "intimacy", especially for auditors in the front seating area. Intimacy is a qualitative term used to describe the extent to which sound appears to come from the screen in a motion picture theater. If the included angle of the sound received by an auditor is small, he will judge the auditorium to have intimacy. In this respect, reflections from the side walls are more significant than those from the ceiling, for ones ability to localize sounds in the horizontal direction is somewhat greater than it is in the vertical direction.

It is good design to utilize the floor area which has the best acoustical environment for seating and to use the poorest areas for non-listening purposes. Thus, whenever possible, the area directly in front of a speaker should be used for seating rather for an aisle.

2. ELEVATION OF SEATS

Since an audience constitutes a highly absorptive surface, sound waves which graze it are greatly attenuated. Hence, it is good design in an auditorium, from the standpoint of hearing as well as of seeing, to elevate the seats in order to provide a free flow of direct sound from the source to the listeners. A good line of sight will do this. The first few rows can be level since they will have a good line for both sight and sound. The higher the source is elevated, the farther back the level area can be extended. Let us denote by d the distance which should not be exceeded between the source and the last row of level seating area. A useful fomula for computing this distance is

$$d = r(2.5h-1)$$

where r is the distance between rows and h is the height of the source.

example:

Suppose the rows are 3 feet apart and that the lips of a speaker are 5 feet above the floor level.

What is the distance of the level area from the speaker?

$$d = 3\,(2.5 \times 5 - 1)$$
$$= 34.5 \text{ ft.}$$

The floor can begin to slope up at any convenient distance which is nearer the speaker. The angle of elevation of the room; in an auditorium, it should not be less than 8°, in a demonstration lecture hall it should be about 15°. It is advantageous not only to elevate the seating area but also to stagger the seats.

3. CEILINGS

The ceiling and walls should provide favorable reflections of sound, especially for the seats far removed from the stage. In some instances, the ceiling also should aid in the diffusion of sound. However, if adequate means of diffusion are furnished by the floor and wall surfaces, no additional diffusion is needed for the ceiling; hence, it may be utilized to the outmost for the advantageous reflection of sound. Lecture rooms chamber music rooms, council chambers, christian science auditoriums are type of rooms which a low smooth, highly reflective ceiling may be used to good advantage.

In general, the ceiling height of a room to be used for speech and music should be about one third to two thirds of the width of the room — the lower ratio for every large rooms, and the higher ratio for small rooms.

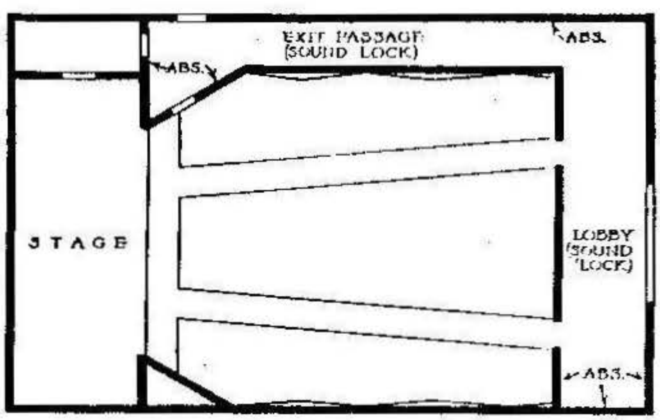
Example: find the ceiling height

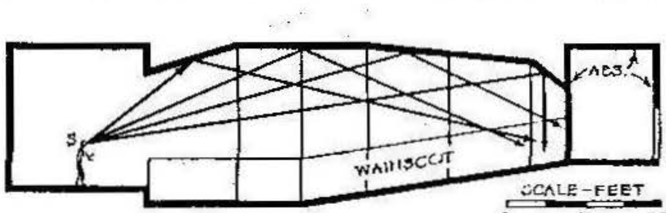
A large room 33 m. wide x 50 m. long use lower ratio 1/3 (33) =11meters.

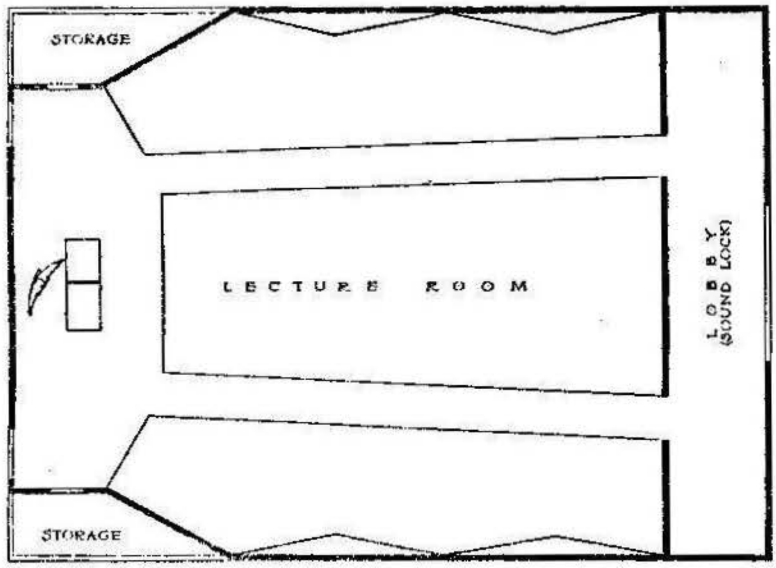
A small room 6.00 x 8.00 m. use higher ratio 2/3 (6.00) =4.00 meters.

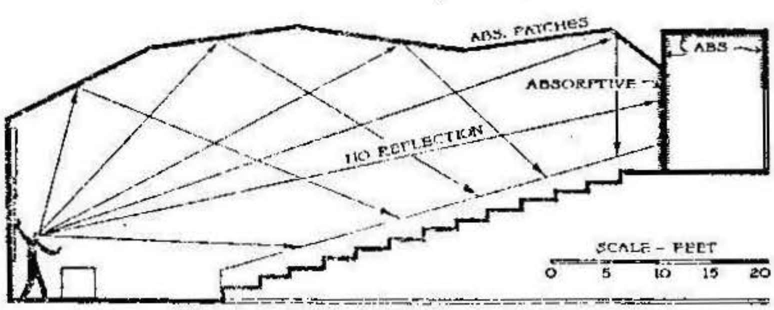
If the ceiling of an auditorium is too high, not only will the volume per seat be excessive, but also long-delayed reflections from this surface will be a source of echoes. (studio design can have higher ceiling heights)

Ceiling splays in the front of a room, or appropriately tilted portions of the ceiling can be devised to reinforce the sound reaching the rear parts of an auditorium.



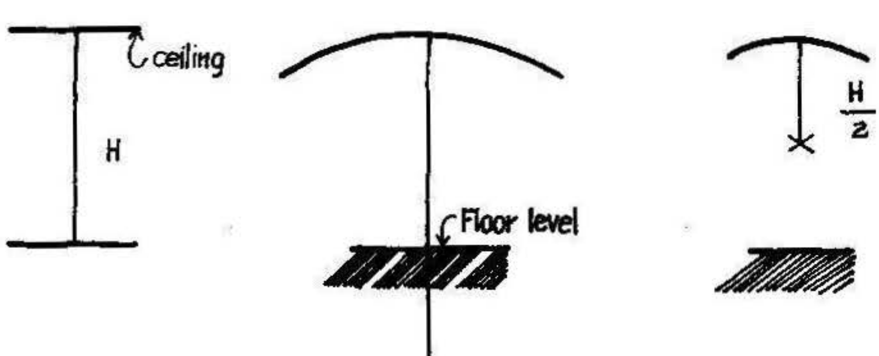




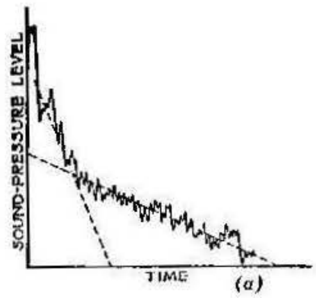


They serve the same purpose as do the front splays of the side walls. The LAW of REFLECTION (angle of reflection equals angle of incidence) can be used to determine the most propitious angle of inclination. Similarly, a splay between the ceiling and the rear wall can be designed to reinforce the sound in the rear of the room, and at the same time to prevent echoes from the rear wall.

Concave surfaces such as domes, cylindrical arches, and barreled ceilings should be avoided wherever possible. If they are required by the architectural style, the radius of curvature should be either at least twice the ceiling height, or less than one-half the ceiling height.



If coves, **bay or other small** concave surfaces are employed, their radii of curvature **should be quite small** compared to the ceiling height. The most serious defects **(sound foci or echoes)** occur when the radius of curvature of a ceiling surface is **about equal to the** ceiling height.



In order to avoid flutter echoes, a smooth ceiling should not be strictly parallel to the floor. If the floor and ceiling are both smooth, level and highly reflective, the flutter between the floor and ceiling will be very prominent.

4. SIDE WALLS

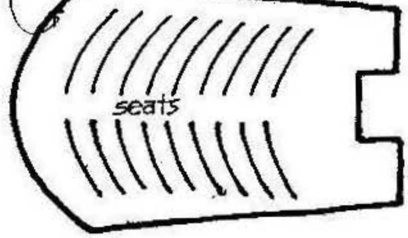
The side walls should reinforce the sound that reaches the rear parts of a large room. This is especially desirable for auditoriums in which a sound-amplification system is not utilized for all spoken and musical programs. The location of the wall is, of course determined principally by the general contour of the floor plans. The angle that any portion of the wall surfaces, such as a splay makes with the wall contour line should be such to reflect sound beneficially to those seats where the sound level is not adequate. The law of reflection can be used to determine this angle. The side walls should be designed so that the sounds they reflect to the audience will not be too long delayed.

Splay — a sloping or beveled surface or angle as of the side of a doorway, a spreading expansion, enlargement

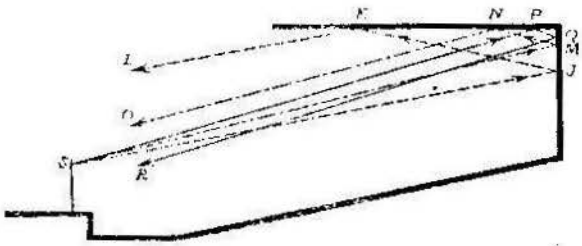
Some parts of the side walls may be suspected of causing probable echoes or unduly delayed reflections; this may happen in very large auditoriums. In such instances the supported surfaces should not be reflective. Instead they should either be made "acoustically rough" to diffuse the sound, or they should be covered with highly absorptive material. Examples of side walls based on good acoustical designing for different types of rooms are given in the chapter of Auditorium design.

5. REAR WALL

In the design of all rooms, large concave rear walls should be avoided.



Unfortunately, they are of common occurence because it seems so simple and economical to most architects to have the rear wall follow the curvature of the last row of seats. Walls with this shape are responsible for troublesome echoes and delayed reflections in many theaters and auditoriums. This is illustrated below which is a longitudinal section showing a vertical rear wall.



Sound rays reflected from the ceiling near the rear wall at P are next reflected from the rear wall at Q to seats in the vicinity of R; there results an echo at R if the path difference at R exceeds 65 feet (about 20 meters). Sound rays striking the rear wall at M are reflected to the ceiling at N, and then to O at the back part of the stage. Often these reflections from concave rear walls are concentrated in regions near the microphones of the sound-amplification system; then feedback trouble is induced. These detrimental reflections can be converted into beneficial ones by introducing a ceiling splay between the ceiling and the rear wall, as shown in the sectional figure below.

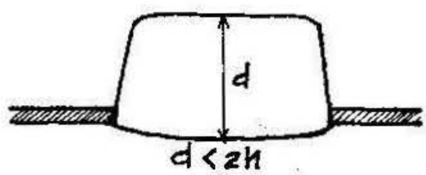
Here the rays SP' and SM' are reflected to the rear seats; thus l or 2 db are added to the sound level in that area. Absorptive material on the rear wall eliminates the echo at R. Concave surfaces in certain situations can be made as effective as splays, and they are sometimes better adapted than splays to the general appearance of the room. However, unless properly designed, they can lead to focusing effects. In some designs, splays between the ceiling and side walls are useful in prevention of long-delayed reflections and in directing advantageous reflections to the audiences.

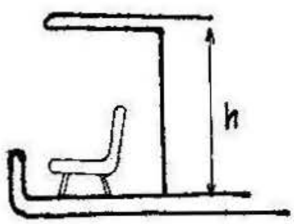
If reflections from either a vertical or tilted wall are capable producing echoes, the offending surface should be treated with absorptive material. There will still be some reflection from this surface, but the sound level is thus reduced so greatly that its detrimental effects are negligible.

In some large rooms, reflection from a portion of the rear wall can be utilized effectively by tilting the wall; for example, see "balcony recess" below. Proper rear wall design can increase the sound level in an auditorium where the increase is most needed. Caution must be observed, however, to avoid the concentration of reflections in small areas, especially for excessive path — length differences between the direct and reflected sounds in rooms where the rear wall is relatively high or where the seating area rises rapidly, it is not advisable to tilt the entire rear wall, to do so might reflect the direct sound toward the front of the room so that echoes could be produced.

6. BALCONY RECESS

Good design of a balcony recess usually requires a shallow depth and a high openings. For an auditorium or legitimate theater, the depth should not exceed twice the height of the opening.



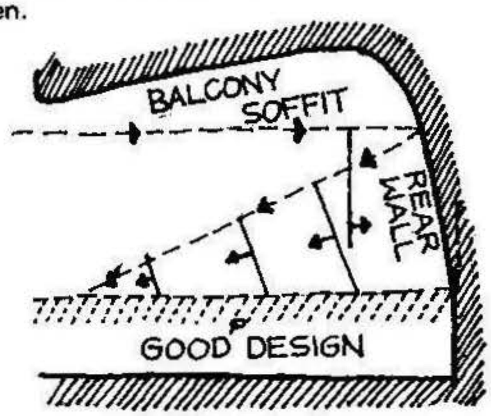


This plan permits sound to flow readily into the space under the balcony. Good design also requires that the reverberation time in the balcony recess approximately that of the main part of the auditorium. (see reverberation in coupled spaces, chapter 5)

By applying the above rules, it is possible to design the recess so that the sound level in this space is about the same as it is in other equally distant parts of the auditorium. However, if the opening is low and the recess relatively deep, the sound level will be considerably lower in this area, especially at the rear of the recess. For example, if the depth is equal to four times the height of the balcony opening, the level may be 8 db lower at the rear wall than it is at the opening. In large auditoriums and theaters, it is advisable to "break up" the rear wall in order to provide proper diffusion of sound throughout the balcony recess. *A large unbroken concave rear wall always should be avoided,* since it invariably gives rise to a non-uniform distribution of sound. Trouble of this kind also may arise from large vertical surfaces of glass in front of the standee rail.

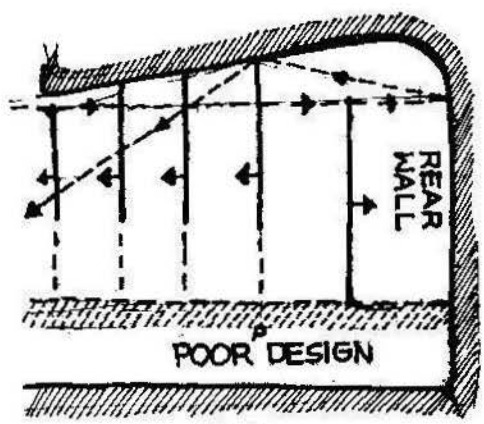
The balcony rail (front) should not be overlooked when the acoustical design of an auditoriums is being worked out. Since it is frequently a large, concave, surface having a width that is large compared to the shorter wavelengths of speech and music, the balcony front can give rise to an echo or "slap back". By tilting this surface downward and making it convex it is sometimes possible to utilize the resulting reflections to increase the sound level at the rear of the auditorium. Otherwise , the front should be highly absorptive or should have a contour such that reflections from it will be diffused and not concentrated in small areas.

The balcony soffit and rear wall should be designed so that a large portion of the sound coming directly from the source will be reflected to the auditors under the balcony, and the remainder absorbed by the rear wall. An example of one such plan is shown in figure (a) below, which is a section of the balcony recess of the philips theater in Eindhoven.



(a)

Measurements made in a scale model indicate that this design leads to a distribution of sound on the floor of the auditorium that is fairly uniform: see figure (b) below.



(b)

If the time lag between the direct sound and the reflections from the rear wall is short, the auditor will not be aware of the direction from which these reflected sounds come. He will have illusion that all the sound comes directly from the stage, for auditory localization is poor in the vertical direction. Furthermore, it is much more difficult to discriminate between sounds coming from directly ahead or behind than between sounds coming from one side or the other. Hence, these reflected contributions may be utilized effectively. In contrast to the section of fig. (a) is the section shown in fig (b). Here the rear wall reflects sound to the front part of the auditorium.

Volume Per Seat

The most desirable volume for a room is closely correlated with the design of the ceiling. There is no fixed optimum ratio between ceiling height and width and length. The optimum height, and therefore the optimum volume per seat, is dependent on both the seating capacity of the room and the purposes the room is to serve.

The optimum volume per seat for a room is the lowest value consistent with the visual and aesthetic requirements, with the comfort of the audience, and with the general appearance. Thus, although it is desirable to have a low value of volume per seat, it should not be attained by seating the auditors so close to each other that they do not have sufficient leg room or by sacrificing other functional features. In motion picture theaters seating 1000 people, the optimum volume per seat may be as small as 125; for theaters with a seating capacity of 2000, the volume not exceed about 175 cu. ft. per seat. In music rooms seating more than 1500, a volume per seat of 200 cu. ft. has been found to give satisfactory results.

There are many advantages in keeping the volume per seat at a low value. The building cost is greatly reduced. Maintenance costs for lighting, cleaning, redecorating, air-conditioning, etc. are correspondingly lowered. There are also important acoustical advantages. Thus, suppose that a given reverberation time is sought. Then, from reverberation time equation of the smaller volume of the room the fewer will be the units of absorption

$$t_{60} = \frac{0.049\ V}{S\,[-2.30 \log_{10} (1 - <]}$$

The smaller the volume of the room the fewer will be be the units of aborption required to obtain this reverberation time. In an auditorium with a low volume per seat; if the furnishings (seats, carpets, draperies, etc.) have been carefully chosen, there may be no need for additional acoustical materials to control the reverberation. Then the architect has greater freedom in this choice of materials for furnishing to interior and for decoration. Also, it follows from equation:

$$< \ = 10 \log_{10} \frac{W}{A} + 136 \text{ db}$$

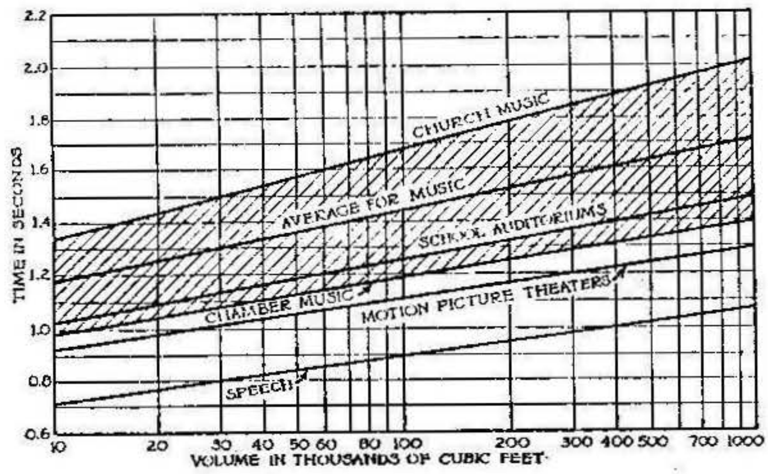
Or steady-state value of sound pressure, that the lower the volume per seat, the higher will be the sound level in the room for a given power. In speech and music rooms where sound-amplification systems are not employed, this increased level is most beneficial. Even if a "sound system" is used, the smaller the room, the smaller will be the required power rating of sound system.

For a given seating capacity, an auditorium design which incorporate a balcony usually has a lower volume than one that does not. Other factors which affect the volume per seat are the arrangement of the aisles, the inclination of the floor, the distance between seats, whether or not the seats are staggered, and the floor plans.

Control of Reverberation Characteristics

The reverberation characteristics of a room can be controlled by the amount and placement of absorptive material within it. The total amount of absorption in a properly designed room determines the rate at which sound decay in it. Proper distribution of the absorption aids in controlling the diffusion of sound and also the nature of the time fluctuations of the sound during its decay.

The first step in planning the acoustical treatment is to determine the optimum reverberation time, from figure (a) and (b), and to find the total number of square-foot-units (sabins) of absorption required to give this time. A large part of this absorption will be furnished by agents other than acoustical materials, for example, the chairs, rugs, audience walls, ceilings. It is customary to assume that the size of the audience in an auditorium will be equal to two thirds of the seating capacity. Then the amount of absorption that must be added is the difference between the total required units and the number of units furnished by the above named agents. (specific example is worked out in the table next page.



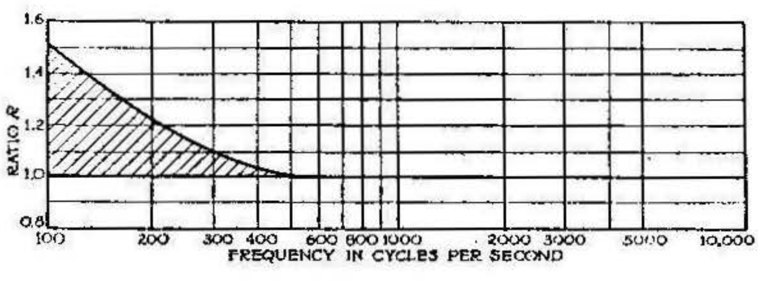


TABLE 15.1

A. Required Absorption

	128 Cycles	512 Cycles	2048 Cycles
Optimum reverberation time in seconds	1.5	1.0	1.0
$-2.3 \log_{10} (1 - \bar{\alpha})$	0.174	0.261	0.261
$\bar{\alpha}$	0.160	0.230	0.230
Total square-foot-units of absorption required = $S\bar{\alpha}$	1200	1725	1725

B. Absorption Furnished by Wall Surfaces

Absorptive Material	128 Cycles		512 Cycles		2048 Cycles	
	Abs. coef.	Abs., in sq-ft-units	Abs. coef.	Abs., in sq-ft-units	Abs. coef.	Abs., in sq-ft-units
Cork carpet, 380 sq ft	0.04	14	0.05	19	0.05	19
Linoleum floor, 2000 sq ft	0.04	80	0.04	80	0.04	80
Ceiling, 2000 sq ft	0.05	100	0.06	120	0.06	120
Wood wainscot, 1060 sq ft	0.06	64	0.06	64	0.06	64
Proscenium opening, 450 sq ft	0.30	135	0.40	180	0.50	225
Stage wall, 430 sq ft	0.05	21	0.06	26	0.06	26
Rear wall, upper side walls 1230 sq ft	0.05	61	0.06	74	0.06	74
Total absorption from above required materials	475		563		608	

C. Absorption Furnished by Unupholstered Chairs and the Audience

	128 Cycles	512 Cycles	2048 Cycles
	Abs., in sq-ft-units	Abs., in sq-ft-units	Abs., in s.q-ft-units
90 unupholstered chairs	27 (0.3 per chair)	27 (0.3 per chair)	27 (0.3 per chair)
180 auditors in unupholstered chairs	360 (2.0 per person)	540 (3.0 per person)	630 (3.5 per chair)
Total absorption by chairs and audience	387	567	657

D. Absorption Furnished by Upholstered Chairs and the Audience

	128 Cycles	512 Cycles	2048 Cycles
	Abs., in sq-ft-units	Abs., in sq-ft-units	Abs., in sq-ft-units
90 upholstered chairs	180 (2.0 per chair)	270 (3.0 per chair)	270 (3.0 per chair)
180 auditors in upholstered chairs	540 (3.0 per person)	810 (4.5 per person)	900 (5.0 per person)
Total absorption by chairs and audience	720	1080	1170

These questions remains: where should be the material be placed) what materials should be used?

As a general rule, the surfaces surrounding the stage should reinforce, by useful reflections, the "voices" of the performers. On the other hand, the rear wall must be designed so that long-delayed reflections from it are prevented from reaching the audience. This requirement usually necessitates the use of a highly absorptive rear wall; the wainscot (should extend not more than about 1 foot above the heads of the audience) should have an average absorption coefficient in excess of 0.75. In auditoriums where the acoustical design indicates the desirability of tilting forward the rear wall (see rear wall no. 5 this chapter) so that reflections from this surface may be beneficially utilized, very much less absorptive material is needed and it should be applied in patches or panels. After allowances have been made for the rear wall treatment, the remainder of the required additonal absorption should be distributed on the side walls, preferably in patches, strips, or panels having dimensions of the order of 3 to 5 ft (for example, note the distribution shown in the figure below) The application of the absorptive material in the form of patches not only promotes diffusion will also helps to suppress flutter. echoes.

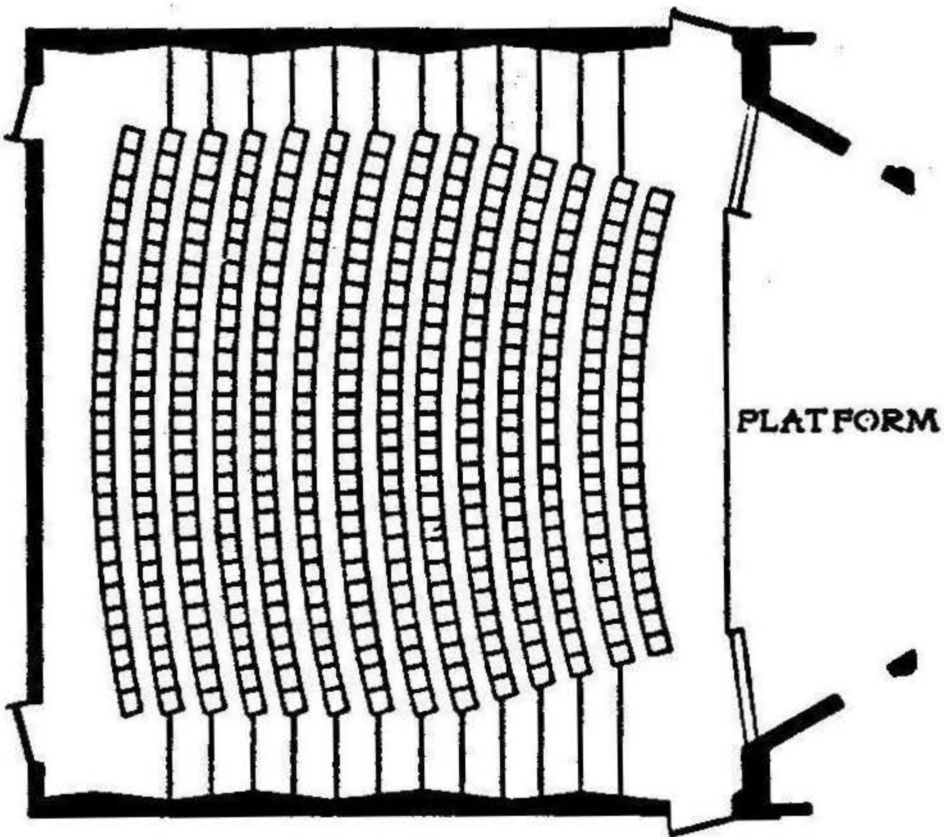
The problem of non-uniform application can be worked out in many ways some examples follows:

(1) Finish the entire wall with a material such as plywood applied to furring strips (taking care to brace the plywood at irregular intervals so that the resonant frequencies of the resulting panels are distributed in frequency). Then perforate some of the panels with small holes and back these perforated panels with an absorptive blanket and thus obtain patches of absorption in such numbers, sizes, and locations as will give the desired reverberation and diffusion.

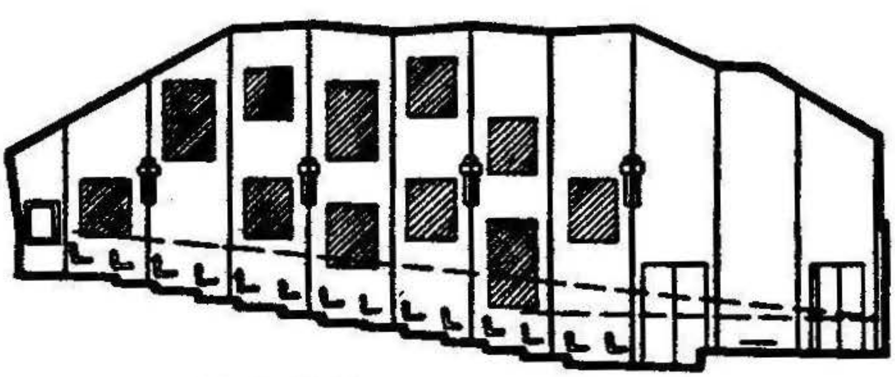
(2) Finish the entire wall or large portions of the wall with perforated board and install absorptive material behind selected portions of the perforated covering. Thus, although the appearance of the surface is uniform, a non-uniform absorptive treatment is obtained.

(3) Treat selected panels, strips (horizontal or vertical), or splays with absorptive material as required to give the optimum reverberation time and good diffusion. If the side walls are treated with absorptive material, the wainscot, should have a height of 4 or 5 ft. The wainscot, if made from a thin flexible material like plywood or flexwood, backed with an absorptive pad or blanket, can furnished low-frequency absorption, which usually is need to provide the optimum reverberation characteristics.

If the chairs are highly absorptive, as they thould be, it usually will not be necessary to add any absorptive material on the rear wall. If the chairs are not absorptive, it may be necessary to add some absorptive to the soffit or side walls of the recess in order to provide the optimum reverberation in this space. When this is done it is desirable to distribute this material in panels, strips, or patches.



PLAN



SECTION

7

SOUND REINFORCEMENT SYSTEMS

OBJECTIVES AND CRITERIA

The purpose of sound reinforcement system is just what the name indicates to reinforce the sound, which would otherwise be inadequate. This an ideal sound system will give the listener the same loudness, quality adjacent to him-a distance of 2 to 3 ft. for speech and further for music depending on type and number of instruments. This situation must obtain for every position in the space except that a variation of ±2 db for loudness is tolerable. The other factors should remain constant. Of these factors, loudness and intelligibility have been discussed at length and should be well understood. By quality we mean that frequency response should be linear so that reproduced sound bears the same relation between its frequency components as the orginal sound. (Quality is then field adjusted by "voicing" by "equalization", which will be discussed below).

Directivity is the characteristic whereby the sound appears to be coming from the originating source, that is, the loudspeakers should be directionally "invisible" and the listener must have the impression of actually hearing the source. It should be emphasized that sound systems cannot correct poor acoustic design completely although they can improve a bad situation.

Generally, sound systems will be required in spaces larger than 50,000 cu. ft. (1500 m^3) 33 ft. x 50 ft. x 30 ft. or ll m. x 16 m. x 9 m. In terms of population, this volume translates as 550 persons in lecture rooms (15 ft. average height and 6 sq. ft. per person) and 325 persons in theaters (20 ft. average ceiling height and 7.5 sq. ft. per person). In such a room (50,000 sq. ft.) a normal speaking voice can only maintain a volume of level of 55 to 60 db, depending on room design and voice strength. With background noise at PNC 35 (see table on suggested noise criteria range for steady background noise on the next chapter on noise) The speaker will be heard; at higher noise levels intelligibility will suffer.

Components and Specifications

All sound systems consist of three basic elements: Input devices, amplifier (s), and loudspeaker systems.

(a) Input Devices

1. *Microphone.* If multiple mikes are required, mixing facilities must be provided.
2. Recorded material from phonograph, tape deck, cassette deck, and possibly commercial music source.
3. Radio source — AM/FM tuner.

(b) Amplifier and Controls

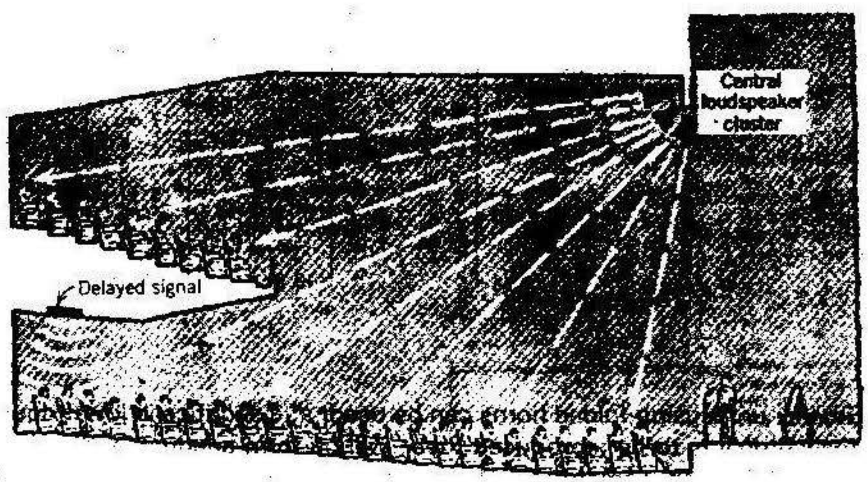
Amplifiers must be rated to deliver sufficient power to produce intensity levels of 80 db for speech, 95 db for light music, and 105 db for symphonic music. This assumes a *maximum* background noise level of 60 db A. Thus, 80 db for speech intensity will be 20 db higher or four times as loud as the noise level. If noise level is known to be below 60 db maximum, amplifier and loudspeaker power ratings can be reduced accordingly. The amplifier should carry technical specs for signal-to-noise ratio; linearity from x to y Hz-3

db, and low (–%) distortion. Exact figures here depend on application and are left to the acoustic specialist or sound engineer to supply.

In addition to the usual volume, tone mixing, and input-output selector controls, the amplifier must contain special equalization controls for signal shaping. These are highly critical filter networks that are used to voice per equalize a sytem after installation. Equalization is a sine qua non of a good sound sytem, without which, the system will howl, sound rough, give insufficient and poorly distributed gain and sound level and generally sound poor. Essentially, voicing tailors the system to the acoustic properties of the space.

A system not equipped for equalization is not a professional system and results will verify it. Furthermore, the specification must provide for the services of a competent sound engineer to perform the equalization after installation and construction is complete.

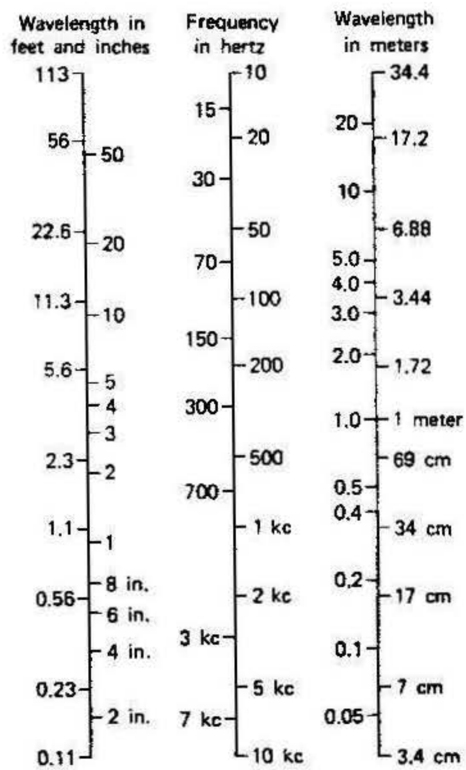
Another control frequently required in theater systems is a delay mechanism or circuit that can introduce a time delay into a signal being fed to a loudspeaker. The figure below shows a sound system that covers a majority of an auditorium from a central — loud-speaker cluster. The underbalcony seating areas are hidden from the central cluster and receive the reinforced sound from distributed loudspeakers in the underbalcony soffit to provide directional realism, the signal to the underbalcony loudspeakers must be delayed to allow the weaker signal from the central speakers to arrive first. Delay is necessary since electrical signals travel at the speed of light whereas sound is much slower (one millionth the speed, approximately). With this arrangement sound will seem to come from the source, and the directivity for necessary to realism is maintained.



(c) **Loudspeakers**

These are the heart of any sound sytem and obviously must be of the same high quality as the remainder of the system. Indeed, system economics will show up much more quickly in loudspeaker performance than in any other component. Selection of speakers is a complex, technical task not within our scope. Nevertheless, a few general remarks are in order.

The best systems use central — speaker arrays consisting of high quality, sectional (multicell), directional, high-frequency horns and large cone woofers. These assemblies are very large, and the architect should be aware of the dimensions that must be accomodated. Units 6 ft. wide, 8 ft. high and 3 ft. deep (1.80 m x 2.40 m x 0.90 m), with a weight of 1000 + lbs are common in a large lecture hall or small theatre. This size is necessitated by the large wavelength of low frequency sound. (see figure below)



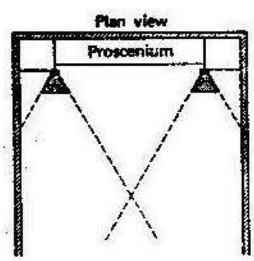
Smaller units using folded horns can be used, at a sacrifice in low-frequency response, if speech only is to be reproduced these will perform adequately distributed systems use small (4-12 inch diameter) low-level speakers, ceiling mounted, and firing directly down to give adequate response these units must be mounted in at least a 2 cu. ft. enclosure. Smaller enclosures will usually seriously compromise performance.

Loudspeaker Considerations

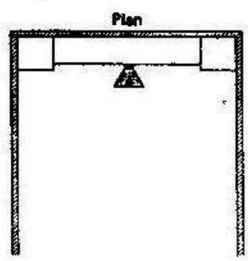
Loudspeaker — system design and placement must be coordinated with the architectural design. The two principal types of loudspeaker systems are *central* and *distributed*. The loudspeakers in a central system are a carefully designed array of directional high — frequency units combined with less directional low-frequency units, placed above and slightly infront of the primary speaking position. In most theaters, this location would be just above the proscenium on the centerline of the room. Located in this position, the system provides directional realism and is simple in its design.

The distributed loudspeaker system consists of series of low-level loudspeakers located overhead throughout the space. Each loudspeaker covers a small area, in a manner similar to downlights. This type of system is used in low-ceilinged areas where a central speaker cluster could not provide proper coverage. It also can be used for public address functions if directional realism is not essential, in spaces as exhibition areas, airline terminals, and offices. In addition, distributed loudspeaker systems provide flexibility for use in spaces where source and listener locations vary accordingly to the use of the space, since loudspeakers can easily be switched to provide proper coverage.

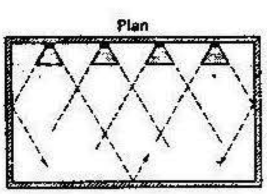
Combination loudspeaker systems that utilize both central and distributed units are used to solve special problems as discussed earlier and illustrated in the figure section of (amplifier and controls). In general, a listening position should receive sound from only one loudspeaker. Systems that cover seating areas with signals from several scattered loudspeakers usually increase the loudness of the sound but tend to produce garbled speech. This rule is the principal reason that the arrangements shown in the figure below will guarantee a bad job. The common practice of placing one loudspeaker on either side of a proscenium opening figure (a) or rows of speakers on or both sides a room figure (b) is particularly to be deplored.



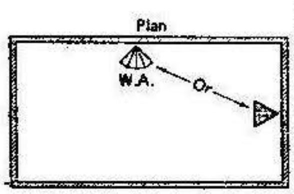
a.
Large, high—level speakers on both sides of a proscenium opening give poor coverage, cancellations, reflections, and no sense of directivity.



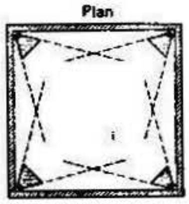
a—1
Proper installation would locate a single high—intensity array, at the center of the room above the proscenium, near the ceiling, and angled down into the audience.



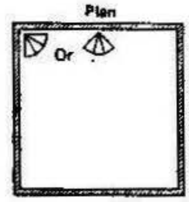
b.
Small wall—mounted speakers yield confused garbled sounds, areas of cancellation, and lack of directivity caused principally by strong reflections from opposite walls.



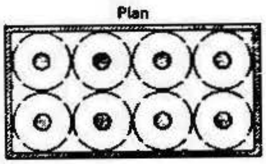
b—1
Proper installation would use a single wide—angle unit facing the long wall or a narrower unit on the short wall. Choice depends on room reverberation and dimensions. Low—level, ceiling—distributed system is also possible if directivity is not important.



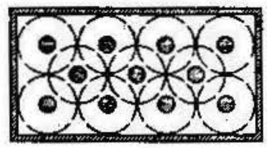
c.
Poor coverage at space perimeter; chaotic sound conditions in the center.



c—1
Proper installation uses a single standard or wide—angle unit depending on room characteristics. Ceiling system not advisable or necessary.

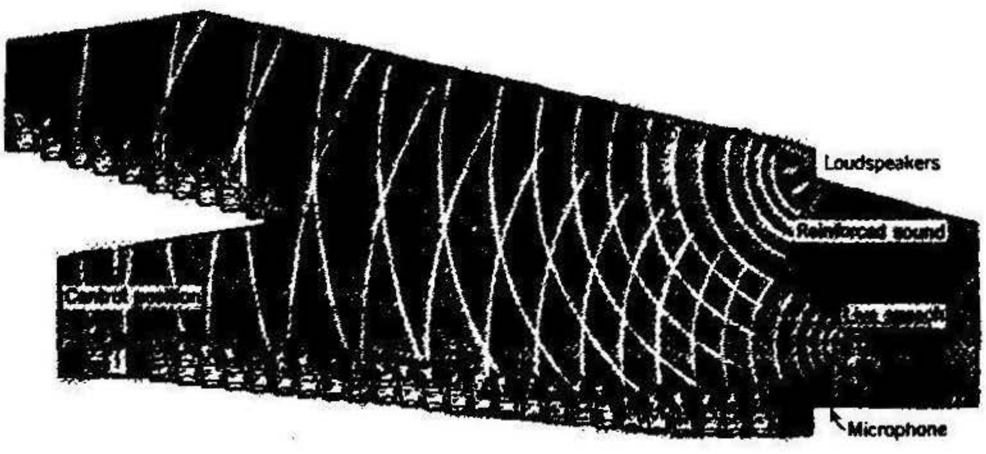


d.
Excessive variations in intensity over the room area.



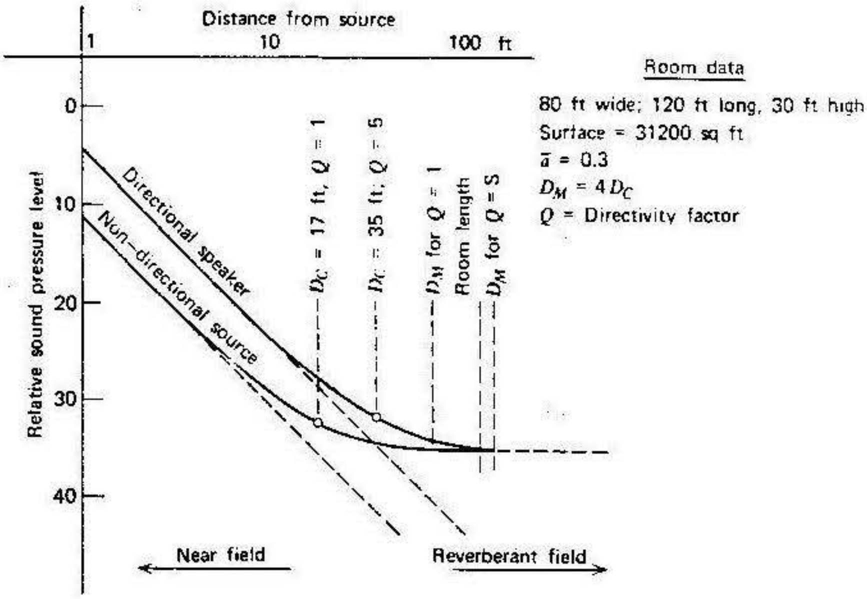
d—1
A staggered pattern gives more uniform coverage in that speakers are closer together. Angle of coverage for low—level speakers is approximately 60°. Coverage circles are drawn on the working plane.

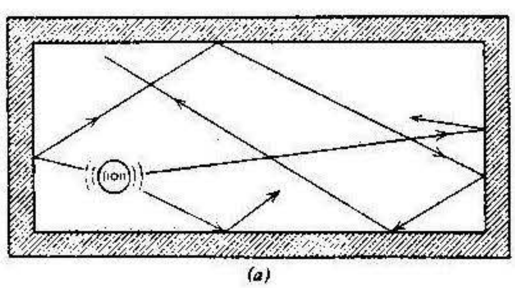
Essential parameters for location and design of the control position create problems for the architect. The sound system operator must be within the coverage pattern of the loudspeakers. For proper operation, he or she should be able to hear the sound as it is heard by the audience. Some current auditorium designs locate sound systems controls within the audience seating pattern (see fig. below)

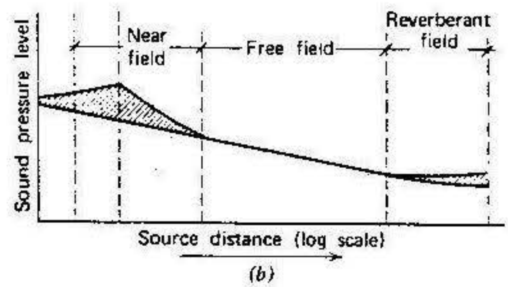


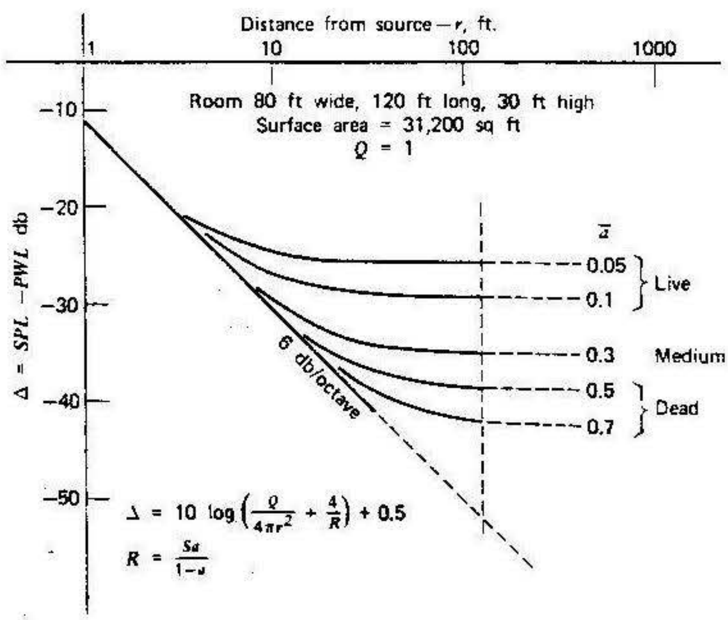
other place a control room with a completely open wall or a large window at the rear of the auditorium. Monitor loudspeaders and earphones are inadequate substitutes for actual listening within the auditorium. In churches the simple control equipment can be located at the rear of the congregation area.

To understand selection and positioning of a high-level directional loudspeaker, it is necessary first to understand its action in a space. Refer to figure next page.


Distance from source
1
10
100 ft
Room data
80 ft wide; 120 ft long, 30 ft high
Surface = 31200 sq ft
$\bar{a}$ = 0.3
$D_M = 4 D_C$
Q = Directivity factor
Relative sound pressure level
0
10
20
30
40
Directional speaker
Non-directional source
D_C = 17 ft, Q = 1
D_C = 35 ft, Q = 5
D_M for Q = 1
Room length
D_M for Q = 5
Near field
Reverberant field


(a)


Sound pressure level
Near field
Free field
Reverberant field
Source distance (log scale)
(b)


Distance from source — r, ft.
1
10
100
1000
Room 80 ft wide, 120 ft long, 30 ft high
Surface area = 31,200 sq ft
Q = 1
−10
−20
−30
−40
−50
Δ = SPL − PWL db
$\bar{a}$
0.05
0.1
Live
0.3
Medium
0.5
0.7
Dead
6 db/octave
$\Delta = 10 \log\left(\frac{Q}{4\pi r^2} + \frac{4}{R}\right) + 0.5$
$R = \frac{Sa}{1-a}$

We have transferred the curve $\bar{a} = 0.3$, that is, a medium (neither live nor dead room) from fig. (b) above, to fig. (a) and have added a loudspeaker curve calculated from equation.

$$a = \frac{S_1 \alpha_1 + S_2\alpha_2 + \dots\dots\dots + S_n \alpha n}{S_1 + S_2 + \dots\dots\dots\dots\dots\dots + S_n}$$

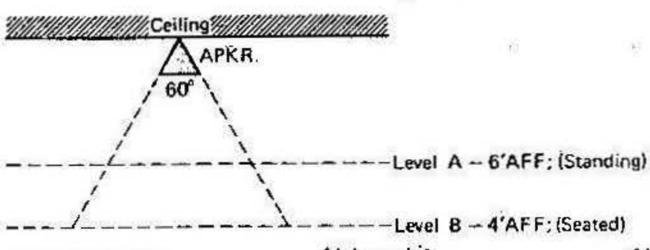
for Q = 5, which is a common figure for multicell directional speakers. Note the result.

First the level in the near field and free field areas have been raised 7 db. Second, the critical distance (Dc) has been doubled, that is, increased from 17 to 35 ft. *Critical distance* is defined as the point at which the distance between the asymptote and actual curve is 3 db. *At that point the direct and reverberant components are equal.* Beyond that point the reverberant field predominates.

We have already stated that to maintain good directivity and clarity the direct component should predominate or at least constitute a large portion of the sound. It is widely accepted that *maximum* distance from loudspeaker to listener should not exceed four items the critical distance for good quality reproduction and comprehension (preferably less) Note the on the figure (a) lower and higher curve, that with Dc at 35 ft. the maximum distance becomes 140 ft. since the room is only 120 ft. long a single high-level directional array is satisfactory. If the room were longer, the rear portions would require additional coverage.

Alternatively room characteristics could be changed by adding absorption to reduce reverberance, C7 is more highly directive loudspeaker could be used. If it is not possible to use a central system, distributed speakers will perform adequately but without directivity. (see table below). These decisions are the province of the acoustics expert, w/o whose expert advice complex or expensive installations should not be designed.

Table 26.7 *Area of Coverage; 60° Cone Loudspeaker Firing Directly Down*



Ceiling Height, Feet	*At Level A*		*At Level B*	
	Diameter[a]	*Area*[b]	*Diameter*	*Area*
8	1.15	4.2	1.7	17
9	1.73	9.4	2.3	26
10	2.31	17	2.9	38
11	2.9	26	3.5	51
12	3.5	38	4.0	67
13	4.0	51	4.6	85
14	4.6	67	5.8	105
15	5.2	85	6.4	127
16	5.8	105	6.9	151

8

NOISE CONTROL

INTRODUCTION

Freedom from the harassing effects of noise is one of the finest qualities a building can possess. The architect is obliged to seek, by every possible means, those features of design and construction that will impart to his building the utility and charm of quiet surroundings. An intelligent approach to the problem of constructing quiet buildings must be based upon a knowledge of:

1. The magnitude, nature and distribution of noise in buildings and out-of-doors.
2. Acceptable noise levels in various types of buildings;
3. The propagation, and especially the *attenuation* (reduction of the energy or intensity of sound) of sound through the free air, through openings and ducts, and through or around obstacles, embankments, and landscaping.
4. The reduction of sound, and the suppression of vibration by varied types of partitions and flexible connectors.
5. The reduction of machinery noise at its source by appropriate selection of equipment from a noise-producing standpoint;
6. The reduction of noise by the proper use of sound-absorptive treatment.

For a room or building in which quietness is a prime requirement, it frequently is desirable to make measurements of the noise at the site as a means of determining the types of structure that are needed to insulate adequately against the prevailing noises. For routine design, however, it is sufficient to make use of the data from noise surveys in buildings and outdoors.

Too frequently the architect overlooks noise control or depends on luck and a few "sound-insulation blankets". The *noise level,* that is, the sound-pressure level of the noise, in speech and music rooms should be low enough so that it will not interfere with the hearing or with the production of speech or music. In offices, factories, and other work rooms, noise should be reduced to levels that will not impair the health, contentment, or efficiency of the workers in these rooms. In restaurants, residences, and hospitals quietness is especially desirable.

In the development of the mechanization of industry, machines of greater power and higher speed, often with correspondingly augmental noise output, replace smaller ones. Undoubtedly, the growth of mechanization has been accompanied by an increase in noise. Although commendable efforts are being made to reduce the noise of machines and appliances, there has been no marked reversal in the upward trend in city and industrial noise. On the other hand, the public is becoming increasingly conscious of the ill effects of noise. The architect and builder, therefore, face a growing need for the reduction and control of noise in buildings.

The harmful effects of noise are well known. Even quite feeble noises interfere with the hearing of speech and music; moderately loud noises produce auditory fatigue; and very loud noises, if long endured, induce permanent losses of hearing. Although the influence of noise on the working efficiency and general health of human beings is generally recognized as harmful, those who have scientifically investigated these effects are not in complete agreement about their nature and extent. There is evidence from one carefully conducted investigation that both the working efficiency and the total output of weavers increased when they wore ear plugs which reduced the noise level from 96 to 81 db.

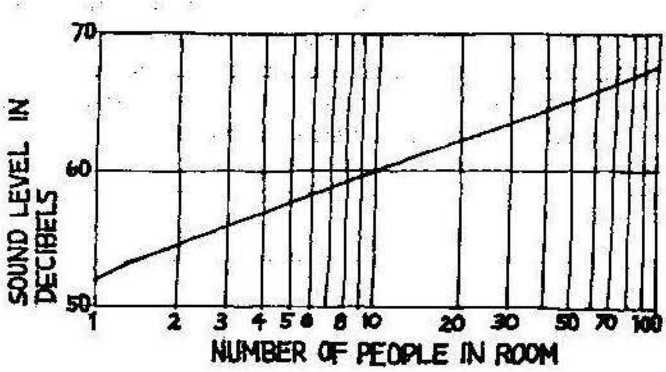
The detrimental effects of the noise were observed to be greatest at the beginning and near the end of work periods, possibly indicating that persons go through a process of adaptation to noise, endure it without noticeable effects for a time, but finally suffer from its incessant attack. The bulk of other evidence indicates that the reduction of noise and reverberation, following the usual acoustical treatment of offices and factories, results increases in output of labor and in human well-being that more than offset the cost of the acoustical treatment. Although it is difficult to measure fatigue, most observers agree that excessive noise exacts a heavy toll in frayed nerves and physical exhaustion.

Among the most frequent "offenses" of noise are the honking of automible horns, barking of dogs, the screaming of ambulance sirens, the late arrival of some members of the family, and the chirping of birds. The wearing of ear plugs, which attenuated these noises about 30 db reduces the total number of awakenings during sleep to less than one half.

Noise in Buildings

The principal sources of rooms may be grouped into three broad classifications: (a) People (b) Machinery and (c) Outdoor sources. The relative noise contributions from these three types of sources depend to a large extent, on the use of the room in which the noises commingle. For example in about 45% of the business locations at which measurements were made, the predominant source of noise was people; in 25% of these locations, machinery was the predominant noise source; and in 30% of them, outside sources were predominant. In factories, the relative percentages were of the order of 10, 80, and 10 percent, respectively. The greater the number of people in a room, the noisiest it is; and, the higher the noise level, the louder an individual must speak in order to be heard above the noise.

This suggests that the effect of acoustical materials in reducing the noise level in a room maybe greater than one might expect; since the absorptive treatment lowers the average noise level, individuals can speak in a lower voice and be heard. Hence, at least part of the noise level (that due to speaking or conversation) is reduced "at its source" as well as by absorption. An approximate relationship between the noise in a business office and the number of people in the room is given in this figure.



These data show that the noise level, in decibels, increases directly as the logarithm of the number of people in the room.

A summary of the average sound-pressure levels of room noise at telephone locations is given in the table below. Since these results are based on measurements in a wide variety of places and consequently include a wide range of noise levels, standard deviations are given. The noise level in residences is generally 3 db lower in colder climates in December than in summer, since closed windows exclude a large part of the noise from outside.

TABLE

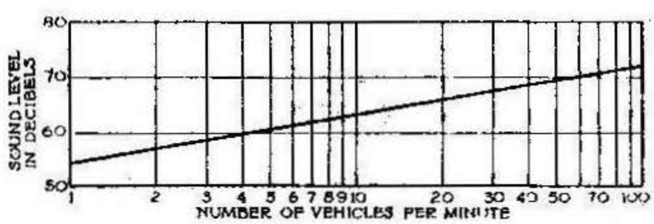
Summary of Annual Average Noise Levels in Rooms in Decibles
(D. F. Seacord)

Type of Location	Average Noise Level	Standard Deviation	Excess of Summer over Winter
Residence			
Without radio	43.0	5.5	3
With radio	50.0	8.0	4
Small store (1 to 5 clerks)	53.5	7.5	4
Large store (more than 5 clerks)	61.0	6.0	0
Small office (1 or 2 desks)	53.5	6.5	4
Medium office (3 to 10 desks)	58.0	6.5	1
Large office (more than 10 desks)	64.5	4.5	0
Factory office	61.5	9.5	−2
Miscellaneous business	56.0	7.5	1
Factory	77.0	12.0	−2

*The levels given in this table are "weighted"; that is, they are the levels measured with a standard sound-level meter incorporating a 40-db frequency-weighting network.

Outdoor Noise

Sounds of outside origin are often the principal contributors to noise in offices, churches, and residences. The largest source of outdoor noise is generally automobile traffic. For this reason it is desirable that all buildings in which quietness is an important factor, including churches, auditoriums, and hospitals, be not constructed near a busy or potentially busy, street. In order to determine the sound-insulation needs of a building so that the planned insulation will meet future requirements, it is desirable to make a noise survey at the proposed site and to estimate the noise contributions from future traffic conditions. In this connection the figure below is of interest.



It shows the relation between the average outdoor noise level (at the street curb). In decibels, vs the flow of street traffic in terms of vehicles per minute. These data indicate that the noise level varies directly with the logarithm of the number of passing vehicles. While automobiles, trucks, street cars, and subways account for the major sources of outdoor noise in most locations, traffic is responsible for the peak noise levels in many areas and should be taken into account in estimating noise-insulation requirements in these localities. For example, in a noise survey at the proposed site of a theater in San Diego, California, where civilian and military planes can be seen and heard overhead during most of the daylight hours, the noise level from the passing planes exceeded 70 db twenty times during a typical one-hour interval. When no planes could be heard, the level was less than 61 db. The maximum level recorded during this typical one-hour period was 90 db, when 18 single-motor planes passed information at about 2000 ft. elevation and at a minimum distance at about 1 ½ miles.

Acceptable Noise Levels in Buildings

The highest level of noise within a building that neither disturbs its occupants nor impairs its acoustics is called the *acceptable noise level.* It depends, to a large extent, on the nature of the noise and on the type and customary use of the building. The time fluctuation of the noise is one of the most important factors in determining its tolerability. For example, a bedroom with an average noise level of 35 db, with no instantaneous peak levels substantially higher, would be much more conducive to sleep than would be a room with an average noise level of only 25 db but in which the stillness is pierced by an occasional shriek. Futhermore, levels that are annoying to one person are unnoticed by another. It is therefore impossible to specify precise values within which the noise levels should fall in order to be acceptable. It is useful, however, to know the range of average noise levels that are acceptable under average conditions.

A complication of such levels for various types of rooms in which noise conditions are likely to be a significant problem is given in this table.

TABLE

Recommended Acceptable Average Noise Levels in Unoccupied Rooms

	Decibels
Radio, recording, and television studios	25-30
Music rooms	30-35
Legitimate theaters	30-35
Hospitals	35-40
Motion picture theaters, auditoriums	35-40
Churches	35-40
Apartments, hotels, homes	35-45
Classrooms, lecture rooms	35-40
Conference rooms, small offices	40-45
Court rooms	40-45
Private offices	40-45
Libraries	40-45
Large public offices, banks, stores, etc	45-55
Restaurants	50-55

The acceptable noise levels of this table are useful in calculating the sound-insulation requirements of walls, partitions and ventilation ducts under typical noise conditions.

Siting and Planning Against Noise

The selection of the site for a building, the layout of the buidling itself, and the grading and landscaping of the site are indespensable parts of good planning against noise in buildings. The existence and persistence of quiet sites is dependent on zoning ordinances and their enforcement. Architects in every community should cooperate with the civic authorities in the segregation of noxious activities including noisy industries, power stations, airports, traffic arteries. From buildings where quiet is an absolute necessity, such as schools, churches, hospitals, and residences. These buildings should be protected by civic planning.

Inter urban automobile and truck traffic should be routed *around, not through,* areas that have been zoned for schools, residences and hospitals; express highways that must pass through zones requiring quiet surroundings should be isolated by means of embankments or parapets along the outer edges of the highways; trains should enter large metropolitan centers by underground routes; parks and landscaping should be planned to impede the propagation of noise into quiet zones; and approaches to airports, which are increasing noise nuisance in all large cities, should be from the *outskirts* of the city, *not over it.* Schools, churches, hospitals, and residences should not be located on noisy highways.

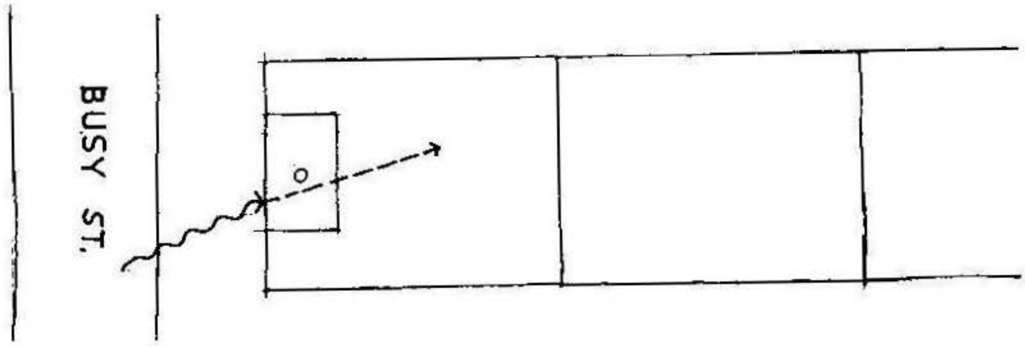
Grading and Landscaping

Anyone who has stood beside a railroad track and listened to the noise from a train as it enters a "cut" where there is an embankment between the listener and the train must have noticed the effectiveness of the embankment in reducing the noise. Thus, an earth embankment or a masonry garden wall often can be used to reduce the noise that impinges on a building and aid in the establishment of quiet conditions within the building without resorting to costly measures of sound insulation. It may reduce the level by as much as 5 db. If the surfaces of the barrier facing the source of noise is absorptive, such as a grassy turf, dense vines, other planting or even leaf mold or peat moss, the over-all noise reduction may amount to as much as 8 or 10 db. Hedges or trees with dense foliage act as sound absorbers and reflectors, and their effectiveness increases with the extent (thickness, height, and density) of growth. A hedge 2 ft. thick has sound-obstructing value of about 4 db.

Building Layout

The location of a building on its site, the arrangement of rooms, corridors and vestibules, and the location of doors and windows, all have a bearing on the control of noise; they require careful consideration. For example, the noise level at the end of a room adjacent to a busy street may be at least 5 db higher than it is at the opposite end. In such a situation it is advantageous to place the speakers platform at the end of the room adjacent to the street, which is the primary source of noise.

This arrangement has two advantages: (1) The more distant parts of the audience are in the quieter section of the room, and (2) a speaker has a natural tendency to raise the level of his voice in the presence of noise.



The side of a building facing streets, playgrounds, or other sources of noise should house those activities that can tolerate the greatest amount of noise, and the sides of the building that face the quieter environment should be reserved for those rooms that require the quietest conditions.

Windows should not open on noisy street or yards. Doors which open on noisy streets should be supplemented by sound locks. While courts can be used to good advantage to shield certain rooms from street noise, they are usually serious offenders in reinforcing (by multiple reflections) the sounds that issue from windows opening on them. Many dwellers in city apartments attribute their sleepless nights to the disturbance from the neighbors radio which blasts its strident noise into a court-a reverberant container that sustains the noise and aids in its efficient transmission from one open window to another.

A noisy room, such as a riveting shop, should be well removed from an office or room where quiet is valued. The doors and windows of adjacent rooms should be as far from each other as possible. It often is advisable to stagger the positions of doors on the two sides of a hall or corridor so that no two doors face each other. Elevators, air-conditioning equipment, motors, and other noise-producing machinery should be removed and isolated from the sections of a building that can least tolerate such noises.

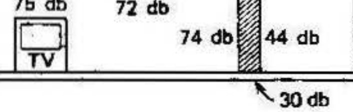
9

AIR-BORNE NOISE REDUCTION

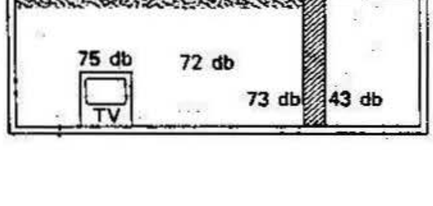
PRINCIPLES OF NOISE REDUCTION

Noise can ruin the acoustics of an otherwise well-planned auditorium. Failure to plan for adequate insulation against noise, in the design of buildings, is almost universal. One of the misconceptions inherent in many proposed methods for sound insulation is based upon the erroneous assumption that materials and methods which are effective for heat insulation are also effective for sound insulation. It is important that the architect and builder recognize that these two separate problems, even though certain types of structures may be effective for both. In general, nearly all porous materials are good heat insulators and good sound absorbers as well. Nevertheless, they are usually poor sound insulators. Porous materials or other types of acoustical treatment can reduce, somewhat, the level of the noise transmitted into a room; but they do not provide the most effective means for insulation against outside noises. It is injudicious and uneconomical to construct a building without proper planning against noise and then to hope that absorptive material will solve the subsequent difficulties.

Noise reduction is essentially the science of converting acoustical energy into another, less disturbing form of energy-heat. Since the amounts of energy involved are minute-130 db corresponds to 1/1000 of a watt or 0.003 Btu, the heat produced is completely negligible. This conversion is by absorption, by the room contents and wall coverings, and by the structure itself. The former controls noise levels within a space and the latter noise transmission between spaces. Noise control treatment within a room will affect the reverberant noise level within that room but will have minimal effect on the noise level in adjoining spaces. Refer to the figures, for a graphic presentation of this fundamental fact.

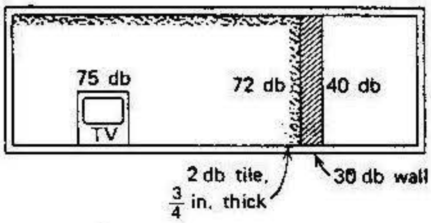


(a) TV set in free space produces 75-db sound level, which drops 6 db for each doubling of distance. Attenuation by inverse-square law (see Section 26.7).

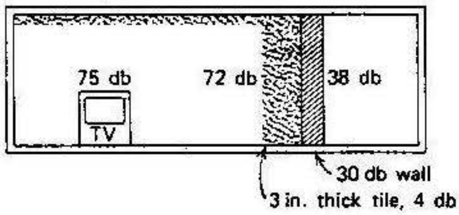


(b) TV still produces 75 db. In the free field, sound drops to 72 db but builds up to 74 db at the wall due to reverberant field reinforcement (see Figure 26.17, page 1175). Wall attenuation is 30 db. Sound on other side of the wall is 74 − 30 = 44 db.

(c) Acoustic tile ceiling acts to reduce room reverberant field. Free field is extruded. Level at wall is 73 db. Level in second space is 73 − 30 = 43 db.



(*d*) Entire room is acoustically treated, effectively eliminating reverberant field. Room is 'dead'. Level on second side of wall is 72 db less acoustic tile loss, less wall loss. (that is, $72 - 2 - 30 = 40$ db.

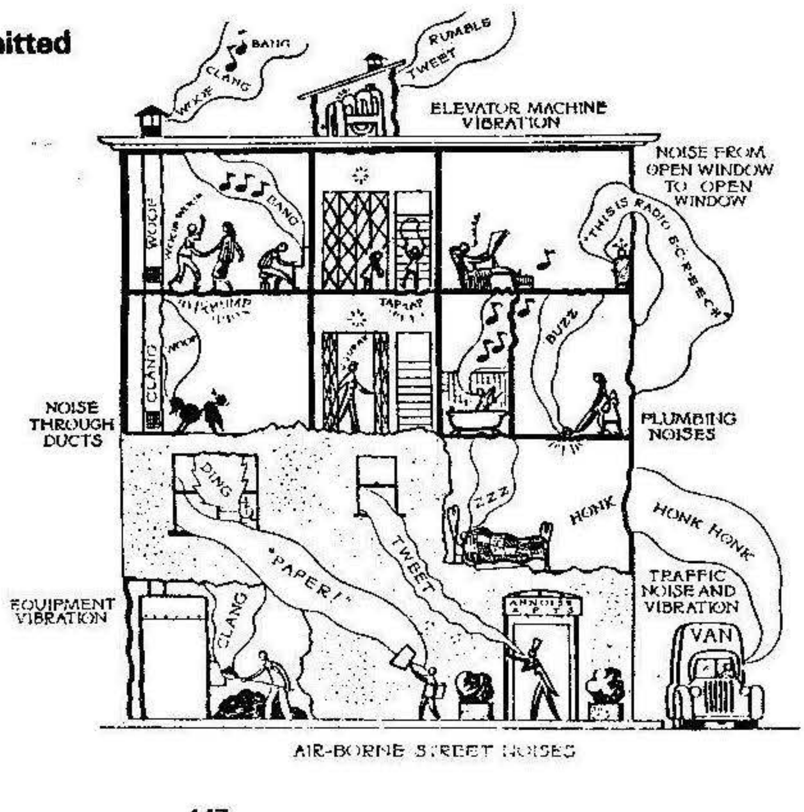


(*e*) Add another $2\frac{1}{4}$ in. of acoustic wall treatment. Room is dead. Level at wall 72 db. Level in second space $= 72 - 4 - 30 = 38$ db.

The best that can be accomplished with acoustic room treatment is elimination of the reverberant field, that is, to make the intensity at the room boundaries what it would have been in free space, as in fig (d). Adding further wall or other acoustic absorbent as in fig. (e) does nothing in the room itself and has minimal effect on the overall transmission loss, since the transmission loss of the acoustic material itself is very low as can be seen in fig. (b).

Reduction of Air-borne Noise

How Sound is Transmitted



AIR-BORNE STREET NOISES

Most sounds that are communicated to a room, either from the outdoors or from elsewhere in the building, are included in one of the following classifications.

1. *Sounds originating in the air which are transmitted*

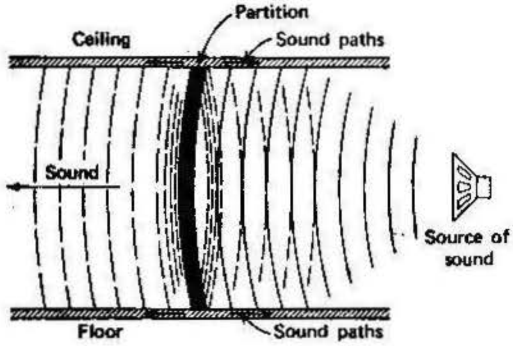
   (a) *Along a continuous air path through openings.* For example: through open windows, elevator shafts, doors, and transoms; through cracks around pipes, electric conduits, telephone outlets; through ventilating ducts.

   (b) *By means of diaphragmatic action of partitions.* Sound waves can force a partition to move back and forth as a diaphragm. By this means, sound from a source on one side of a wall can be communicated to the opposite side.

2 *Sounds originating from direct impacts*

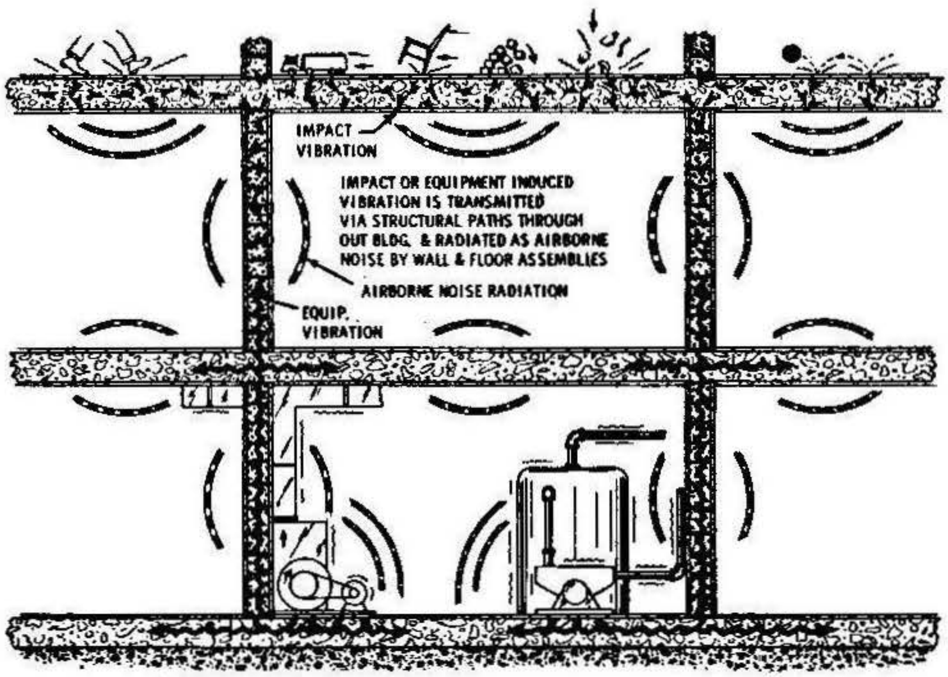
(for example, impulses produced by the dropping of objects on a floor, the scuffling of feet, footballs, or the slamming of doors), or from *machinery vibrations* are transmitted through rigid structures with almost no attenuation. As a result of a direct impact in one room, large surfaces (such as walls) elsewhere in the building can be set into vibration, thereby radiating acoustical energy in a manner similar to the action of a sounding board on a piano.

These two types of sound transmission differ in many respects. Impacts generate impulses of short duration but large power; these are often propagated long distances. Sound originating in the air generally are of much smaller power, persisting for a longer duration; they usually are greatly attenuated by divergence, and by intervening partitions, so that their disturbing influence is confined to regions near their origin. The methods of insulating solid-borne impact sounds are somewhat different from those of insulating air-borne sounds; a structure that is a very good insulator for one type may be very poor insulator for the other. The general topic of the insulation of impact-generated sounds is discussed next chapter.



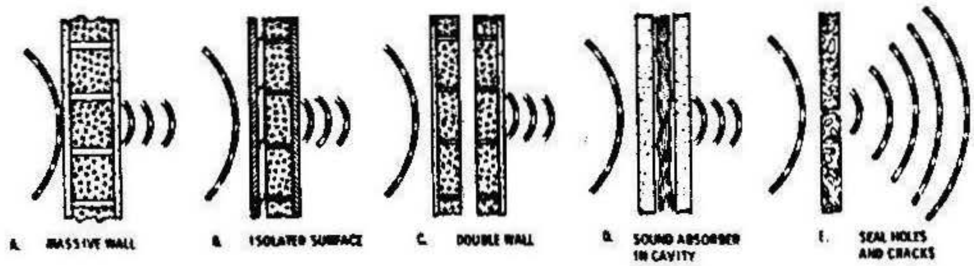
(a)

fig. (a) This sound is air-borne, originating in the air at one side of the partition. The incidence of sound energy causes the partition to vibrate, generating sound on the other side. Sound does not "pass through" – it causes the structure to become a secondary source. The partition vibrates primarily on the direction of the sound.



Transmission of Impact and Structure–Borne Noise.

(b)



(c)

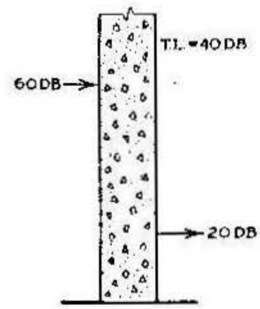
Transmission Through Openings

Noise can be readily communicated from one portion of a building to another through openings such as windows or open doors, frequently these openings limit the total amount of insulation which can be attained. Thus, if it is necessary to open windows for ventilation, the sound insulation between two adjacent rooms may be limited by the open windows to 20 db or even less. Under such circumstances, it would be profitless to provide separating partitions of relatively high insulation. Even very small openings, such as cracks around doors or windows, are effective in transmitting sound. This is emphasized by the following example.

Suppose that outdoor noise is transmitted into a room through an opening 10 inches wide and that the transmitted sound in the room attains a level of 60 db. By reducing the opening to a width of I inch, the acoustical power transmitted through it will be decreased tenfold. (diffraction being neglected). In other words, the level of the transmitted sound will be lowered to 50 db. A further reduction in the width of the opening to 0.1 inch (diffraction being neglected again) would lower the noise level another IO db. Thus, according to the above consideration, a reduction in the width to one one-hundredth of its initial opening decreases the level of the transmitted sound only 20 db. It is apparent, therefore, that a high degree of sound insulation requires the complete closing of cracks around windows, doors, pipes, and conduits.

Sound-Transmission Loss (TL) and Noise Reduction (NR)

The sound-insulative merit of a partition is generally expressed in terms of its *transmission loss* in decibels. The transmission loss is equal to the number of decibels by which sound energy which is incident on a partition is reduced in transmission through it. For example, the transmission loss (abbreviated T.L.) of the wall shown in the figure is 40 db. This incident sound energy which strikes this partition is reduced by 40 db in transmission through it; that is, only 1/10,000 of the incident energy is transmitted through the wall. The larger the value of T.L. for a partition, the greater the sound insulation it provides.



The number that is of greater importance to the building designer is the actual noise reduction between two spaces separated by a barrier of transmission loss TL, that is, the action of the barrier in situ. This isolation or noise reduction is defined as

$$NR = IL_1 - IL_2 \text{db}$$

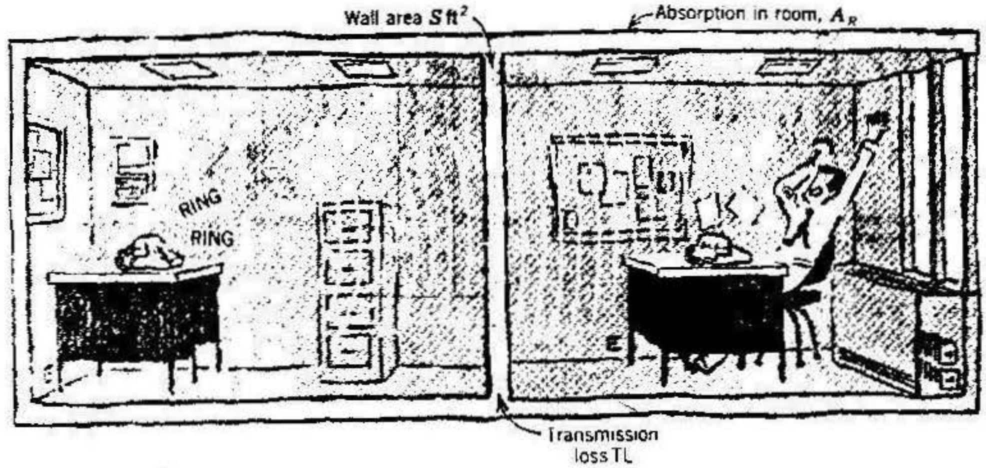
where NR = noise reduction between spaces in db
IL_1 = sound intensity level in source room db
IL_2 = sound intensity level in receiving room db

and is related to the TL of the barrier by the expression

$$NR = TL - 10 \log \frac{S}{A_R}$$

where NR = noise reduction in db
TL = barrier transmission loss in db
S = Area of barrier wall in sq. ft.
A_R = total absorption of receiving room, in sabins

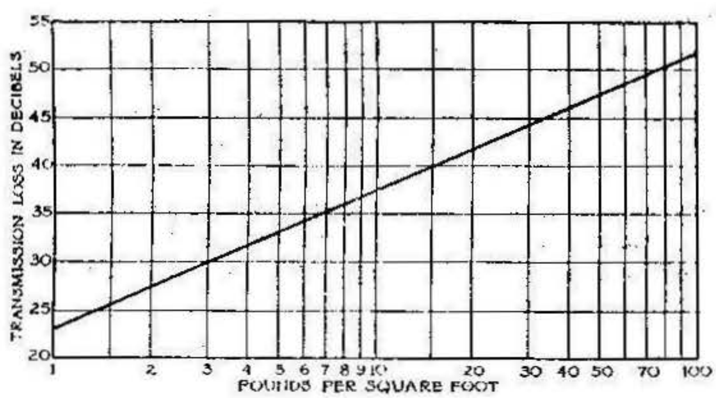
We see, therefore, that noise reduction and transmission loss are not equal but are related by the size of the dividing wall S and the absorption characteristic of the receiving room A_R. A moment's thought will confirm the logic of this relation. When sound energy impinges on the wall, the wall in turn becomes the sound source, radiating into the receiving room. The sound level in the receiving room is related to its own reverberance (absorption characteristic A) as we have seen repeatedly. Thus if the receiving room is a reverberant live space, A is low and the NR is considerably less than TL. Conversely, if the receiving room is dead, A is large and noise reduction can be greater than transmission loss, depending on the ratio of barrier wall size to room area. The figure illustrates the relationships and demonstrates that the vital consideration is not transmission loss but noise reduction.



Rigid Partitions

The transmission of sound through a "rigid" partition, such as a brick, concrete, or solid-plaster wall, is accomplished principally by the forced vibrations of the wall; that is, the entire partition is forced into vibration by the pressure pulsations of the sound waves against it. The vibrating structure thus becomes a secondary source of sound and radiates acoustical energy in to the space on the opposite side of the partition. As one would suppose, the more massive the wall, the more difficult it is for sound waves to move it to and fro. This is a less technical, and less exact, way of saying that most partitions in buildings (walls, ceilings, and floors) are "mass-controlled" over the greater portion of the audible-frequency range. The insulative properties of a partition at low frequencies are partially dependent on its resonant frequencies, which are principally determined by its mass, stiffness, and internal damping.

The manner in which the insulation value of a rigid partition depends on the mass per unit area of the structure is shown by the curve of the figure below.



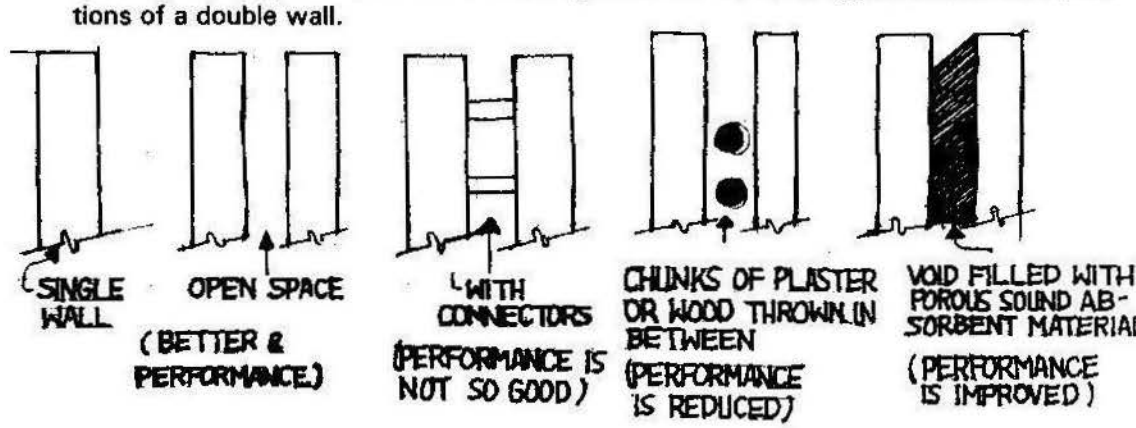
The transmission loss (averaged over the frequency range from 128 to 2048 cycles) is plotted against the weight in pounds per square foot of wall section. It will be noted that the curve approximates a straight line. The slope indicates that *the average* T.L. *of a rigid mass-controlled partition increases 4.3 db each time its weight is doubled.* Thus, the average T.L. for a rigid wall which weighs 10 pounds per square foot of wall section is about 37.4 db; the T.L. for a rigid wall which weighs 20 pounds per square foot is about 41.7 db; and the T.L. for a rigid wall which weighs 40 pounds per square foot is about 46 db. Individual wall structures may depart considerably from average values indicated. However, the average increase in T.L., for each doubling of weight of the partition, will generally be from 4 to 5 db. In the case of a thin flexible panel, such as a window pane, not only the mass but also the stiffness, the internal damping, the size of the panel, and the manner in which its edges are fastened contribute to its transmission-loss characteristics.

Because of the relatively slow increase in sound insulation with the increase in mass of a rigid partition, it is not always practical to secure a high degree of insulation by merely increasing the thickness of the wall. It would be necessary for a concrete wall to be nearly 2 feet thick in order for the wall to have an average T.L. of 60 db. On the other hand, two lightweight walls *isolated from each other* can be designed to provide this same amount of transmission loss. *Where a large amount of sound insulation is required, it is most practical to employ discontinuous construction or compound partitions.*

Compound-wall Constructions (Cavity Walls)

We have seen that the transmission loss in decibels of solid masonry or monolithic partitions increases directly with the weight per square foot of wall section. For walls having a mass of more than 15 pounds per square foot the increase in T.L. with an increase in weight is relatively small. It will be remembered that each successive doubling of the weight of the partition adds but 4 to 5 db. For this reason it is often economical to substitute two or more lightweight partitions that are isolated from each other for a heavy-masonry partition where relatively high value of transmission loss is required.

Double-wall construction frequently offers the most practical means of obtaining high insulation at moderate cost and reasonable dead load. The separate partitions should be as completely isolated from each other as possible. *Structural ties between the separate partitions tend to convert the compound partition into a single rigid partition and thus reduce the sound insulation.* In this connection, it is important to make sure that pieces of wood chunks of plaster, and other building materials are not dropped between the partitions of a double wall.



The number of points at which the two partitions are tied together should be held to a minimum, and the ties should be of a flexible nature. Staggered-stud construction provides structural separation and therefore is often beneficial. The suspension of an absorptive blanket or fiberboard between double partitions, or between the wood studs or channel irons in staggered-stud partitions, may be a substantial aid to insulation if the two partitions are structurally separated. The absorptive material should not make a rigid or semi-rigid bridge between the two partitions for then it may actually lower the sound insulation of the structure.

The effectiveness of the absorptive material depends somewhat on the absorption already present between the walls. In double walls which are not structurally separated, a slight additional insulation may be obtained by the introduction of an absorptive blanket, especially in lightweight partitions. However, this added insulation may not be economically worth while.

Windows and Doors

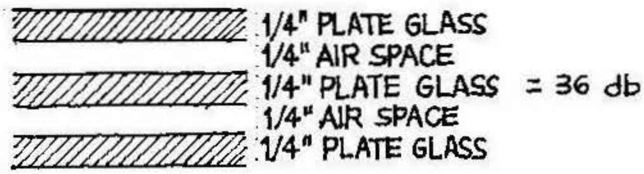
Windows and doors are usually the "paths of least resistance" in the over-all sound insulation of a room. Therefore, they should be given careful consideration for buildings in which good insulation is required.

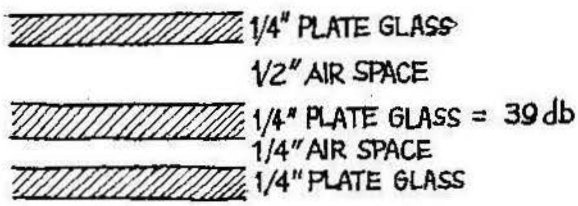
The positions of windows ought to be carefully planned so that, without sacrificing utility or beauty, they are removed as far as possible from other windows in adjacent noisy rooms or from street noise. It is even helpful to hinge the frames of a window which swings outward, so that the panes reflect in a direction away from the window of the adjacent room, sound passing through the open window. Good sound insulation is virtually impossible unless doors and windows fit tightly in their frames; and threshold cracks must be eliminated.

The average transmission loss of a window depends primarily on the thickness of the pane; the heavier the glass, the more insulation it provides. At frequencies well above the lowest resonant frequency of the pane, the average sound insulation increases with increasing frequency. It is not possible to give precise values for the transmission loss of various windows because the T.L. depends, to a considerable extent, on the area of the panes and on the manner in which they are set. (ex: a 1/8" T.L. = 28, 1/4" plate glass. T.L. =31, 3/16 sheet glass: 1/4" air space: 3/16" glass =33, if 1/2" air space =36) these are taken from the average range of 128 tO 2048 cycles.

Double panes are frequently used to increase the sound insulation of a window. To be most effective, the panes should be structurally isolated. However, this is usually impractical except in double-wall constructions. If the spacing between rigidly mounted panes is as little as 1/4 inch, the transmission loss through the multiple structure will be about the same as it would be through a single pane having a weight per unit area equivalent to that of the combination. Increasing the air space increases the transmission loss considerably (as mentioned in the example above). Thus, enlarging the spacing between double-strength (1/4 inch) plate-glass panes from 1/4 inch to 1/2 inch will add about 3 db of sound insulation. If the two panes are not rigidly joined at the edges but are set in felt or rubber, and if the panes fit tightly against the felt or rubber so that there are no "leaky" threshold cracks, the T.L. will be increased at least 4 to 5 db. Increasing the separation between the two panes from 1/2 inch to 6 inches may add as much as 10 db to the transmission loss.

Double pane windows, and sometimes triple-pane windows with 6 inches or more separation between the sheets of glass, are required in special rooms where excellent sound insulation is needed — for example, in radio studios. In such rooms the periphery of the space between panes should be lined with sound-absorptive material. This may add as 5 db to the transmission loss of the window. Each window should be set in felt or rubber, and it is advisable to tilt one pane with respect to the other. A tilt of as little as 1 inch in 12 inches will suffice to suppress high transmission of certain resonant frequencies. Also, by selecting window panes of different thicknesses (so their resonant frequencies are different), a more uniform insulation *vs* frequency characteristic will be obtained.





The transmission loss of a DOOR increases with increased weight; the T.L. also increases with frequency. Most doors of ordinary construction have an average transmission loss of 20 to 25 db; some specially manufactured doors have T.L.'s as high as 40 db. The general trend of the T.L. frequency characteristics follows approximately that of the corresponding curve for rigid partitions. The effectiveness of any door in providing sound insulation depends largely on the seal around the edges. For example, tests on one steel door showed that the placement of a rubber strip on the outer step of the jamb increased the T.L. 4 db. A force of 400 pounds on the panel made still better contact at the edges, and the T.L. was increased another 4 db. The average T.L.'s for a number of different types of doors are given below:

Doors solid 1 3/4", with cracks as ordinarily hung

256 cycles = 15 db
512 cycles = 20 db
1024 cycles = 22 db

solid 1 3/4" welll seasoned and airtight

256 cycles	= 18 db
512 cycles	= 21 db
1024 cycles	= 26 db

Wood, heavy, approximately 2½" thick, rubber gaskets around sides and top; special felt strip pushes down as door closes, eliminating any crack under door; 12.5 lb per sq. ft.

256 cycles	= 30 db
512 cycles	= 29 db
1024 cycles	= 25 db

Noise Insulation Requirements

In Sweden requirements regarding sound insulation have been in force since 1946. The Swedish regulations specify the minimum transmission losses against air-borne sound for partitions and floor-ceiling constructions given below.

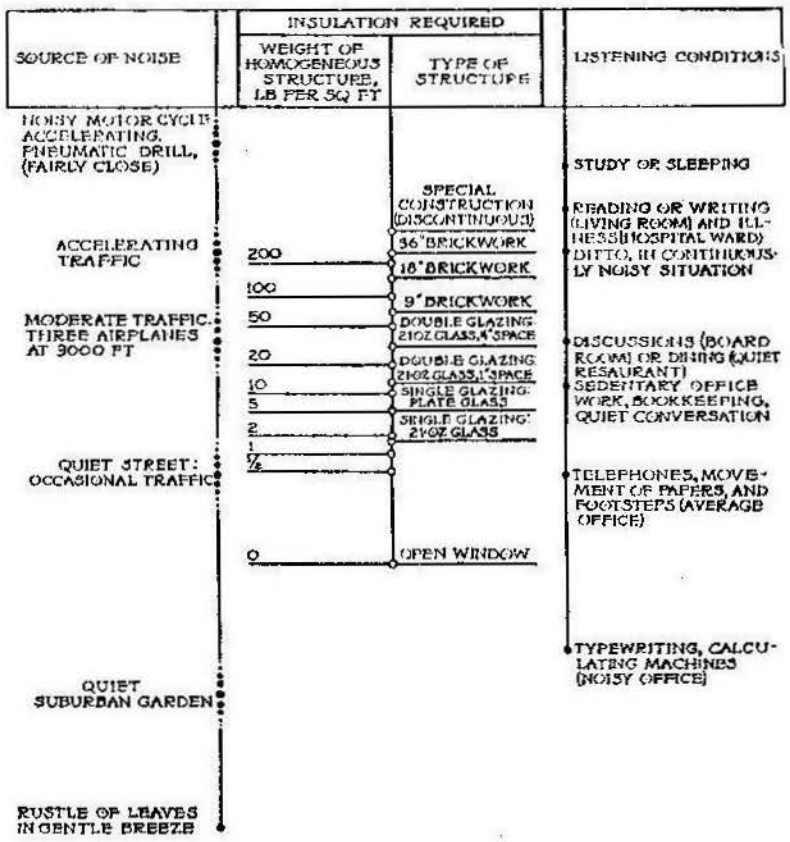
AVERAGE MINIMUM INSULATION REQUIREMENTS IN DECIBELS*

	Frequency Range		
Type of Room	100-500 cycles	500-3000 cycles	100-3000 cycles
Hospitals	44	56	50
Dwelling rooms	42	54	48
School rooms	36	48	42
Work rooms	34	46	40

*Transmission loss measured in decibels with sound-level meter incorporating an appropriate frequency-weighting network.

Noise-insulation requirements for rooms and buildings should be calculated just as routinely as are reverberation requirements; often they *are much more important.* The nomogram in the figure below is an aid in the determination of the approximate minimum insulation requirements. Average noise conditions which may exist outside the room are listed in the column at the left of the chart. The acceptable noise conditions are listed in the column to the right. Insulation needs are estimated in the following way. After an estimate or survey of the exterior noise conditions, the appropriate level on the scale to the left is selected. This point is connected by a straight line through a point on the scale to the right which corresponds to the desired noise conditions. Then the point of intersection of this straight line with that of the center scale determines the approximate minimum insulation requirement. The weight (in pounds per squarefoot of wall section) of a single rigid partition that will provide this insulation is indicated.

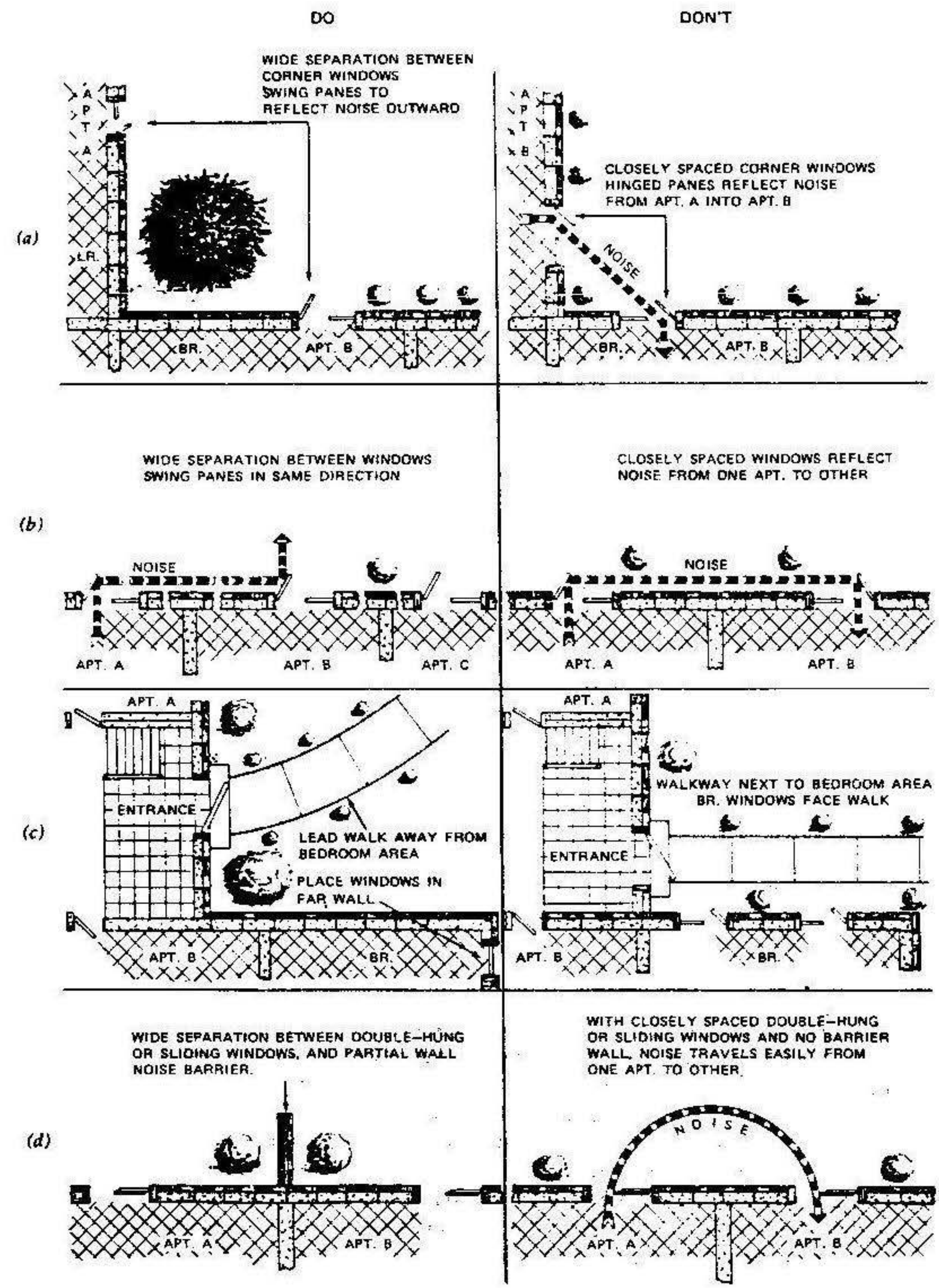
In many cases, it is advisable to utilize a compound partition having an equivalent transmission loss. The use of this figure will yield the minimum average requirements for insulation against conditions of noise. This nomogram should be regarded only as an *aid* in establishing an approximate lower limit of the amount of sound insulation required to meet specified conditions — not as the final means for determining the types of wall construction, doors, windows, etc., that will give satisfactory sound insulation.



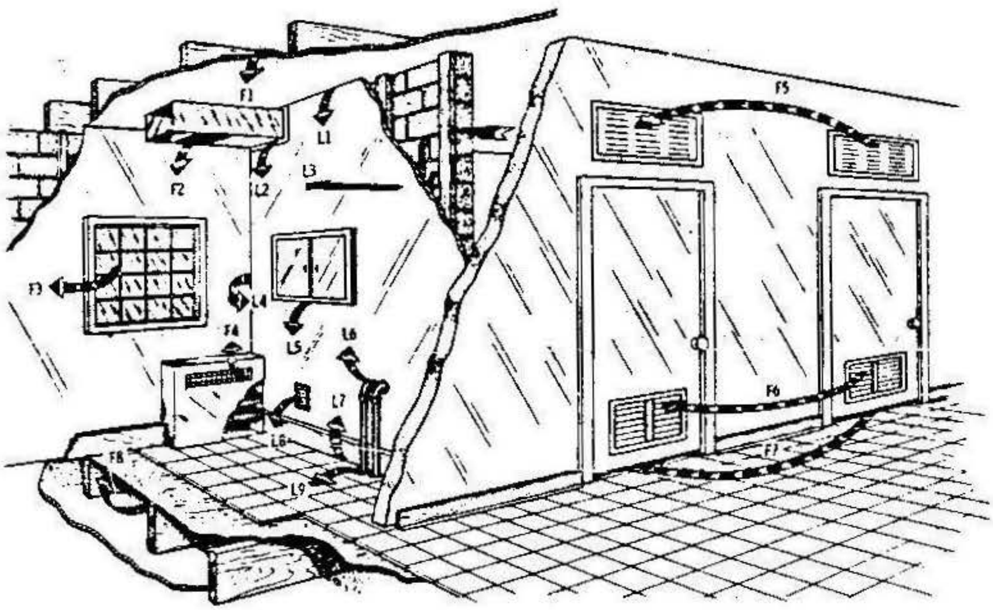
The following working rule for noise-insulation factor has proved satisfactory: *Subtract the acceptable noise level from the average level* (averaged overtime) of the outside noise, to this difference add 10 db. The result is the noise-insulation factor required to furnish adequate sound insulation. The additive term of 10 db is included (1) to provide some protection against disturbances from the usual surges of outside noise that are above the average level, and (2) to allow for unavoidable differences between the sound insulation provided by the actual structures and those determined by laboratory tests on model partitions. For example, if the average level of outside noise is 70 db, and a noise level of 35 db is acceptable in the room, the noise-insulation factor should be about 45 db.

Flanking

Just as sound will pass through the acoustically weakest part of a composite wall, so it will also find parallel or flanking paths, that is, an acoustic short circuit. Proper design of window locations to avoid flanking paths shown in the figure below.



The same situation obtains with respect to doors and any other openings between spaces. Thus, in this next figure, a high STC (sound transmission class) wall between the two spaces is in large measure defeated by flanking paths F5, F6, and F7. In office spaces the most common flanking path via the plenum, as in the figure below Path F1, and the next figure (b) and (d). Ductwork with registers or grills in various rooms acts as an excellent intercom system unless completely lined with sound absorptive material. Even then low-frequency sound is only minimally attenuated, and special measure must be employed if good transmission loss is required.



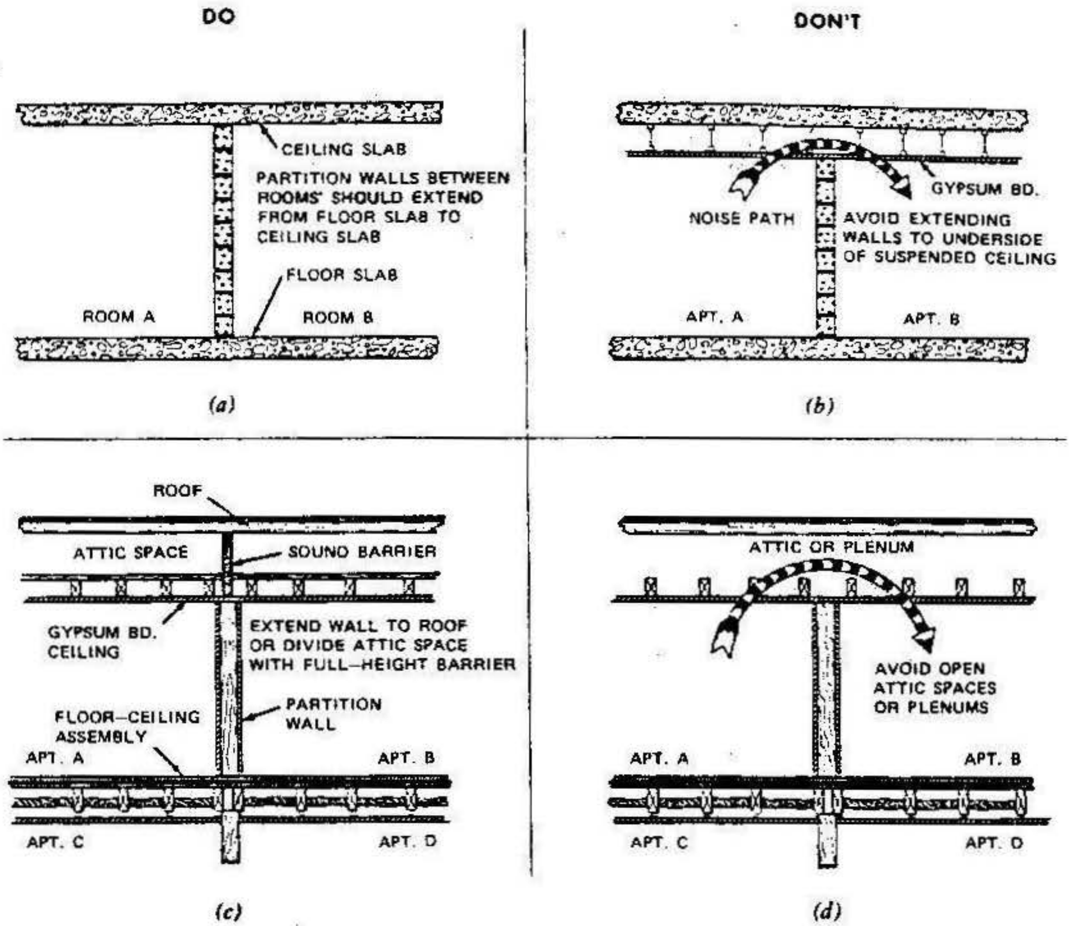
FLANKING NOISE PATHS

F1 OPEN PLENUMS OVER WALLS, FALSE CEILINGS
F2 UNBAFFLED DUCT RUNS
F3 OUTDOOR PATH, WINDOW TO WINDOW
F4 CONTINUOUS UNBAFFLED INDUCTOR UNITS
F5 HALL PATH, OPEN VENTS
F6 HALL PATH, LOUVERED DOORS
F7 HALL PATH, OPENINGS UNDER DOORS
F8 OPEN TROUGHS IN FLOOR-CEILING STRUCTURE

NOISE LEAKS

L1 POOR SEAL AT CEILING EDGES
L2 POOR SEAL AROUND DUCT PENETRATIONS
L3 POOR MORTAR JOINTS, POROUS MASONRY BLK
L4 POOR SEAL AT SIDEWALL, FILLER PANEL ETC
L5 BACK TO BACK CABINETS, POOR WORKMANSHIP
L6 HOLES, GAPS AT WALL PENETRATIONS
L7 POOR SEAL AT FLOOR EDGES
L8 BACK TO BACK ELECTRICAL OUTLETS
L9 HOLES, GAPS AT FLOOR PENETRATIONS

OTHER POINTS TO CONSIDER, RE: LEAKS ARE (A) BATTEN STRIP A/O POST CONNECTIONS OF PREFABRICATED WALLS, (B) UNDER FLOOR PIPE OR SERVICE CHASES, (C) RECESSED, SPANNING LIGHT FIXTURES, (D) CEILING & FLOOR COVER PLATES OF MOVABLE WALLS, (E) UNSUPPORTED A/O UNBACKED WALL BOARD JOINTS (F) EDGES & BACKING OF BUILT-IN CABINETS & APPLIANCES, (G) PREFABRICATED, HOLLOW METAL, EXTERIOR CURTAIN WALLS.

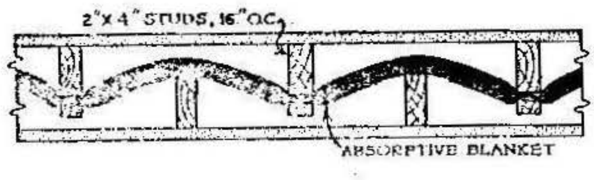


Sound-Insulation Data

Examples

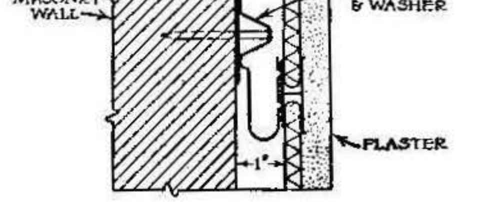
(1) WOOD-STUD AND STEEL STUD PARTITIONS — This type includes wood-stud and steel-stud partitions faced with plaster on wood, metal, or gypsum lath, or faced with fiberboard, plywood, or similar materials. These partitions generally provide greater insulation than do rigid masonry walls of the same weight; but cracks or other openings will greatly reduce their insulation value. Sound is transmitted through such walls principally by setting one facing into vibration (except for the sound transmitted through holes, cracks, etc.) This vibration is then communicated to the second facing, mainly through the studs, and to a lesser extent by the air between these facings. Staggered stud construction, therefore, is better than single-stud construction. Suspended absorptive blankets between the staggered studs, as in the figure, usually increase the transmission loss — especially if they are covered with heavy paper, or similar material, on one or, preferably, on both sides. The blanket should provide a complete septum over the extent of the entire partition. The use of such blankets as a means of increasing the sound in-

sulation in walls is usually economical only in staggered-stud or in structurally isolated double-wall constructions.



(2) BRICK, TILE, MASONRY, AND POURED-CONCRETE PARTITIONS. In this group are included brick, poured concrete, glass blocks, concrete blocks, clay tile, gypsum tile, and other masonry partitions. Their insulation characteristics are approximately those of rigid partitions. Porous blocks, when plastered, usually have a transmission loss which is 3 or 4 db greater than that predicted by the curve discussed earlier in rigid partitions. If the porous blocks are not plastered, they may be very poor insulators; sound "leaks" through the interstices of the blocks. If porous materials are used in wall constructions, the interstices should be of the non-communicating type; that is, each cavity should be completely enclosed. A 4-inch hollow tile, although not adequate for most purposes of sound insulation, can give relatively high insulation if plastered surfaces are furred out from the tile. The more isolation between the plastered surfaces and the tile, the better is the insulation. For example measurements show that one construction of plaster on lath, which was tied (with wires which had been embedded in mortar joints) to 4-inch hollow clay tile, rated slightly better than a solid 8-inch brick wall.

(3) PARTITIONS WITH RESILIENT ATTACHMENT OF LATH. These are constructed of lath fastened to studs by special nails or resilient clips; see figure. Such walls provide somewhat more insulation than do those in which the lath is nailed to the studs in the usual manner. The special nail or clip reduces the "coupling" between the plastered lath and the plastered lath and the studs, thus reducing the vibrational (acoustical) energy communicated to the opposite side of the partition.



Noise Reduction By Sound-Absorptive Treatment

The level of noise which is transmitted into a room is reduced relatively little by sound-absorptive treatment. Acoustical materials are not a cure for poor sound insulation. However, they are extremely useful, and frequently indispensable, in controlling noise through corridors from one room to another. If the noise level is reduced 3 db, the sound level of speech can be reduced about the same amount — Thus the acoustical power expended in speaking can be reduced by a factor of 2.

The installation of acoustical materials in a room has the following beneficial effects:

(1) It reduces the reverberation time, usually several fold;
(2) It reduces the over-all noise level;
(3) It tends to localize noise to the region of its origin (a distant source is attenuated relatively more than one near-by). Since unexpected noises are particularly annoying, this reduction of remote sources of sound is especially helpful.

(1) CALCULATION OF NOISE-LEVEL REDUCTION.

It follows from a consideration of equation

$$L = 10 \log_{10} \frac{W}{A} + 136 \text{ db}$$

where W = acoustical power output of the source in watts
a = total absorption in sabins
L = sound pressure level

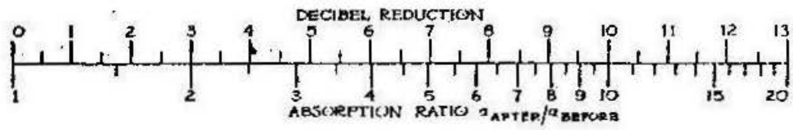
that, if the output of the sources of noise within a room remains constant, the reduction of the noise level (of diffuse sound) due to the installation of absorptive material is given by

$$\text{Noise reduction} = 10 \log_{10} \frac{a_{after}}{a_{before}} \text{ db}$$

where: a_{after} = total number of square-foot-units (sabins) of absorption in a room after treatment, and

a_{before} = total number of sabins of absorption in room before treatment

Thus, if the absorption in a room is doubled, the average noise level will be decreased by 3 db. The noise reduction equation above is expressed graphically in this figure



Since the absorption coefficient of acoustical materials and the pressure spectrum level of room noise both vary with frequency, the reduction will be different at different frequencies. However, to arrive at a single figure which is somewhat representative of the noise-level reduction, it is customary to employ *noise-reduction coefficients* in such computations. The *noise-reduction coefficients* (N.R.C.) of a material is the average, to the nearest multiple of 0.05, of the absorption coefficients at 256, 512; 1024 and 2048 cycles.

As a numerical example, we shall compute the noise reduction in an office 35 feet by 49 feet by 10 feet (11 M x 15 M x 3 M) which results from the treatment of the entire ceiling with a material having an N.R.C of 0.55. The untreated ceiling and walls have a plaster surface whose N.R.C. is 0.03; the floor has an N.R.C. of 0.04, in addition, there are 39 sabins of absorption due to desks, chairs, and miscellaneous items. Hence, the quantity a_{before} is computed as follows:

	Area in Square feet		N.R.C.		Units of Absorption in Square Feet
Floor	1715	x	0.04	=	69
Walls	1700	x	0.03	=	51
Miscellaneous				=	39
Ceiling	1715	x	0.03	=	51
Total			a_{before}	=	210

If the ceiling is covered with a material having an N.R.C. of 0.55, the increase in absorption is 1715 x 0.52 = 892 square-foot-units. Then, the value of a_{after} is 210 + 892 = 1102 square-foot-units. From the noise reduction equation

$$NR = 10 \operatorname{Log}_{10} \frac{a_{after}}{a_{before}} \text{ db}$$

the noise reduction attributable to the installation of the acoustical material would be approximately 7 db. The reverberation time would be reduced from 3.9 second to 0.7 second.

(2) **Noise Reduction by Absorption**

As described earlier, the noise levels in a room are highest for a given source if the room's surfaces are primarily sound reflecting and lowest if there are large areas of sound-absorbing materials. Sound-absorbing ceilings, floors, (carpets), and walls (permanent treatment or curtains) keep spaces such as restaurants relatively quiet. In the distant (reverberant) field of a noise source, the noise level in most room is

$$IL = PWL - 10 \text{ Log } \Sigma S\alpha + 6 \text{ db}$$

or

$$IL = PWL - 10 \text{ Log} \Sigma A + 6 \text{ db}$$

Where:

$\Sigma S\alpha = \Sigma A$

= Total Absorption in room, sabins

IL = Intensity level, decibels

PWL = Sound power level, decibels

Although increasing absorption decreases the noise level, the level never is reduced below the free field level for that distance from the source. (See the first figure, principles of noise reduction, this chapter).

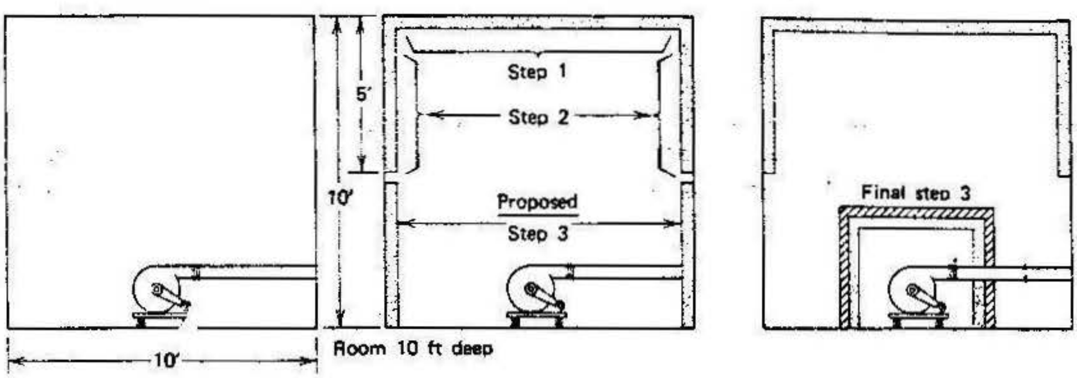
$$\text{Noise reduction} = IL_1 - IL_2$$

$$= \text{Log } \Sigma A_2 - 2A_1$$

$$NR = 10 \text{ Log } \frac{\Sigma A_2}{\Sigma A_1}$$

where ΣA_1 = absorption initial condition, sabins

ΣA_2 = absorption final condition, sabins



(a) (b) (c)

Example:

Referring to the above figure, calculate the original noise level and the subsequent noise reduction by three steps of sound absorption treatment.

Solution:

(a) Original Condition: Painted Concrete Block Chamber

$10 \times 10 \times 10$ ft.

Fan Power Level

At 500 H_z = 88 db

At 2000 H_z = 78 db

Absorption	Area	α	Total Absorption ($\Sigma S\alpha$)
500 H_z	600 ft^2	0.06	36 Sabins
2000 H_z	600 ft^2	0.09	54 Sabins

(see table in the next pages, coefficients of Absorption

Sound Pressure level before treatment

At 500 H_z:

$$\begin{aligned} IL &= \text{Sound Power} - 10 \log \Sigma S\alpha + 6\text{db} \\ &= 88 \text{ db} - 10 \log 36 + 6 \text{ db} \\ &= 88 \text{ db} + 15.6 \text{ db} + 6 \text{ db} \\ &= 78.4 \text{ db} \end{aligned}$$

At 2000 H_z:

$$\begin{aligned} IL &= 78 \text{ db} - 10 \log 54 + 6 \text{ db} \\ &= 78 \text{ db} - 17.3 \text{ db} + 6 \text{ db} \\ &= 66.7 \text{ db} \end{aligned}$$

Explanation:

Looking at the coefficients of absorption Table next page, under concrete block painted refer to the 500 H_z at see the intersection. It gives α = 0.06 then referring to 2000 H_z, it gives α = 0.09 since the area is 600 ft^2, 600 x 0.06 = 36 sabins and 600 x 0.09 = 54 sabins. The area 600 sq. ft. was taken as a total of six (6) sides 10 ft x 10 ft = 100 sq. ft. x 6 sides.

(b) Ceiling Treatment Only:

At 500 H_z;

$\alpha = 0.82$

Additional Absorption $= 100\ (0{,}82 - 0.06)$

$= 76$ sabins

Ceiling is 10 ft x 10 ft = 100 sq. ft.

$$NR = 10 \text{ Log } \frac{76 + 36}{36}$$

$$NR = 4.9 \text{ db}$$

At 2000 H_z:

$\alpha = 0.94$

Additional Absorption $\Delta A = 100\ (0.94 - 0.09) = 85$

$$NR = 10 \log \frac{85 + 54}{54}$$

$$NR = 4.1 \text{ db}$$

(c) Ceiling and one-half wall treated

At 500 H_z:

Added Absorption $= 300\ (0.82 - 0.06)$

$= 228$ sabins

total area of wall (from fig. b)

5 x 10 = 50 x 4 walls = 200

10 x 10 = 100 ceiling

200 + 100 = 300

$$NR = 10 \log \frac{228 \times 36}{36}$$

$= 8.7$ db.

At 2000 H_z:

Added absorption $= 300\ (0.94 - 0.09)$

$= 225$ sabins

$$NR = 10 \log \frac{225 + 54}{54}$$

$= 7.5$ db.

(d) Ceiling and full wall treatment

At 500 H_z:

$$\Delta A = 500\,(0.82 - 0.6) = 380 \text{ sabins}$$

$$NR = 10 \log \frac{380 + 36}{36} = 10.6 \text{ db.}$$

Walling $= 10 \times 10 = 100$

100 x 4 walls = 400 + 100 ceiling = 500 sq. ft.

At 2000 H_z:

$$\Delta A = 500\,(0.94 - 0.09) = 425 \text{ sabins}$$

$$NR = 10 \log \frac{425 + 54}{54} = 9.5 \text{ db.}$$

Summary

	IL	
	500 H_z	2000 H_z
Bare Room	78.4	66.7
Ceiling Treated	− 4.9 db	− 4.1 db.
One-half wall treatment	− 8.7 db.	− 7.5 db.
Full-wall treatment	−10.6 db.	− 9.5 db.

We would conclude here that the third step is really not worthwhile, since only a negligible additional decibel of quieting is accomplished. This example is intended to indicate the law of diminishing returns in quieting by absorption. Starting with a live room, the initial application is effective. Beyond and that, additional is quieting by absorption is not economical, and the same outlay would be better applied in quieting the machine itself, probably with a machine enclosure as indicated in fig. c.

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Table 27.1 *Coefficients of Absorption—α*

Complete tables of coefficients of the various materials that normally constitute the interior finish of rooms may be found in the various books on architectural acoustics. The following short list will be useful in making simple calculations. Items are arranged in alphabetical order.

	Coefficients							
General Building Materials and Furnishings	*125 Hz*	*250 Hz*	*500 Hz*	*1000 Hz*	*2000 Hz*	*4000 Hz*	*NRC*[a]	*Note*
Brick, unglazed	0.03	0.03	0.03	0.04	0.05	0.07	0.005	
Brick, unglazed, painted	0.01	0.01	0.02	0.02	0.02	0.03	0.00	
Carpet, heavy, on concrete	0.02	0.06	0.14	0.37	0.60	0.65	0.29	
Same, on 40-oz hairfelt or foam rubber	0.08	0.24	0.57	0.69	0.71	0.73	0.55	
Same, with impermeable latex backing on 40-oz hairfelt or foam rubber	0.08	0.27	0.39	0.34	0.48	0.63	0.37	
Concrete block, coarse	0.36	0.44	0.31	0.29	0.39	0.25	0.35	
Concrete block, painted	0.10	0.05	0.06	0.07	0.09	0.08	0.05	
Fabrics								
Light velour, 10 oz/sq yd, hung straight, in contact with wall	0.03	0.04	0.11	0.17	0.24	0.35	0.15	
Medium velour, 14 oz/sq yd, draped to half area	0.07	0.31	0.49	0.75	0.70	0.60	0.55	
Heavy velour, 18 oz/sq yd, draped to half area	0.14	0.35	0.55	0.72	0.70	0.65	0.60	
Floors								
Concrete or terrazzo	0.01	0.01	0.015	0.02	0.02	0.02	0.00	
Linoleum, asphalt, rubber, or cork tile on concrete	0.02	0.03	0.03	0.03	0.03	0.02	0.05	
Wood	0.15	0.11	0.10	0.07	0.06	0.07	0.10	
Wood parquet in asphalt on concrete	0.04	0.04	0.07	0.06	0.06	0.07	0.05	
Glass								
Large panes of heavy plate glass	0.18	0.06	0.04	0.03	0.02	0.02	0.05	
Ordinary window glass	0.35	0.25	0.18	0.12	0.07	0.04	0.15	
Gypsum Board, ½ in. nailed to 2 x 4's 16 in. o.c.	0.10	0.08	0.05	0.03	0.03	0.03	0.05	
Marble or Glazed Tile	0.01	0.01	0.01	0.01	0.02	0.02	0.00	
Openings								
Stage, depending on furnishings			0.25–0.75					
Deep balcony, upholstered seats			0.50–1.00					
Grills, ventilating			0.15–0.50					
Plaster, gypsum or lime, smooth finish on tile or brick	0.013	0.015	0.02	0.03	0.04	0.05	0.05	
Plaster, gypsum or lime, rough finish on lath	0.14	0.10	0.06	0.05	0.04	0.03	0.05	
Same, with smooth finish	0.14	0.10	0.06	0.04	0.04	0.03	0.05	
Plywood Paneling, ⅜ in. thick	0.28	0.22	0.17	0.09	0.10	0.11	0.15	
Water Surface, as in a swimming pool	0.008	0.008	0.013	0.015	0.020	0.025	0.00	
Air, sabins per 1000 cu ft @ 50% RH				0.9	2.3	7.2	—	
Rough wood as tongue and groove cedar	0.24	0.19	0.14	0.08	0.13	0.10	0.14	

(Continued)

Acoustic Absorptive Materials	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	NRC[a]	Note
	Coefficients							
Fiberglass Painted Ceiling Boards,[d] textured, $\frac{5}{8}$ in. thick	0.68	0.88	0.70	0.91	0.97	0.93	0.85	2
$\frac{3}{4}$ in. thick	0.66	0.85	0.72	0.94	0.99	0.98	0.90	
1 in. thick	0.69	0.91	0.79	0.99	0.99	0.99	0.90	
Random fissured, $\frac{5}{8}$ in.	0.64	0.82	0.68	0.86	0.83	0.57	0.80	
Perforated, $\frac{5}{8}$ in.	0.71	0.89	0.68	0.90	0.96	0.98	0.85	
Fiberglass Glass Cloth Ceiling Board[d]								
Nubby, $\frac{3}{4}$ in. thick	0.75	0.91	0.70	0.93	0.99	0.99	0.90	
1 in. thick	0.68	0.93	0.77	0.99	0.99	0.99	0.90	
Fiberglass prefinished ceiling tile[d]								
$\frac{5}{8}$ in. thick	0.70	0.83	0.62	0.78	0.91	0.92	0.80	
Celotex Mineral Fiber Tile[e]								
Natural fissured $\frac{3}{4}$ in. thick (Fig. 27.10a)	0.47	0.49	0.51	0.75	0.86	0.80	0.65	
Textured $\frac{3}{4}$ in. thick (Fig. 27.10*b*)	0.49	0.55	0.53	0.80	0.94	0.83	0.70	
Plaid design $\frac{3}{4}$ in. thick (Fig. 27.10c)	—	—	—	—	—	—	0.70	
LeBaron design, $\frac{3}{4}$ in. thick, (Fig. 27.10*d*)	—	—	—	—	—	—	0.70	
Striated design, $\frac{3}{4}$ in. thick, (Fig. 27.10*e*)	—	—	—	—	—	—	0.70	
Perforated lay-in panel $\frac{5}{8}$ in. thick (Fig. 27.10*f*)	0.27	0.26	0.52	0.75	0.68	0.53	0.55	
Gold Bond, National Gypsum[f] Mineral Fiber Tiles and Panels								
"Fire Shield" Solitude Panels, washable acrylic finish								
Perforated $\frac{5}{8}$ in. thick	0.25	0.29	0.60	0.83	0.71	0.53	0.60	
Fissured $\frac{5}{8}$ in. thick	0.28	0.32	0.65	0.73	0.73	0.75	0.60	
Textured $\frac{5}{8}$ in. thick	0.28	0.36	0.65	0.62	0.44	0.33	0.50	
Perforated Asbestos Panels, 1 in. thick								
Uniform	0.60	0.65	0.49	0.71	0.73	0.51	0.65	
Random	0.56	0.51	0.49	0.68	0.60	0.31	0.60	
"Acoustimetal" perforated metal panel, enameled, 1$\frac{5}{16}$ in. thick								
Square pattern	0.59	0.85	0.88	0.99	0.97	0.79	0.90	
Diagonal pattern	0.63	0.84	0.86	0.99	0.99	0.91	0.90	
"Tectum" Sound Blocks								
3 in. thick x 15$\frac{1}{2}$ in. square	0.32	0.60	1.43	2.36	2.32	2.41	1.68	3

Table 27.1 ***Coefficients of Absorption—α(Continued)***

Absorption of Seats and Audience	Values given are in sabins per square foot of seating area or per unit[g] 125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	NRC[a]	Note
Audience, seated in upholstered seats, per sq ft of floor area	0.60	0.74	0.88	0.96	0.93	0.85	—	
Unoccupied cloth-covered upholstered seats, per sq ft of floor area	0.49	0.66	0.80	0.88	0.82	0.70	—	
Unoccupied leather-covered upholstered seats, per sq ft of floor area	0.44	0.54	0.60	0.62	0.58	0.50	—	
Wooden Pews, occupied, per sq ft of floor area	0.57	0.61	0.75	0.86	0.91	0.86	—	
Chairs, metal or wood seats, each, unoccupied	0.15	0.19	0.22	0.39	0.38	0.30	—	
Students in tablet-arm chairs	0.30	0.42	0.50	0.85	0.85	0.84	—	

[a]Noise Reduction Coefficient is the arithmetic average of the α values at 250, 500, 1000, and 2000 Hz.
[b]Installed in hung ceiling with at least 16 in. to slab.
[c]Clipped or glued to wall; minimum 24 in. O.C.
[d]Courtesy of Owens-Corning Fiberglas.
[e]Courtesy of Celotex-Jim Walter Co.
[f]Courtesy of Gold Bond/National Gypsum.
[g]When the audience is randomly spaced, use an average of 5.0 sabins per person.

Absorption Recommendations

To summarize the above discussion, absorption techniques are useful and effective:

a. To change room reverberation characteristics.

b. In spaces with distributed noise sources such as offices, schools, restaurants, and machine shops.

c. In spaces with a hard surface and little absorptive content.

d. Where listeners are in the reverberant field. (no amount absorptive material can reduce intensity levels in the direct field)

Concentrated noise sources are better handled by individual equipment enclosures than by room treatment, since enclosures reduce direct field noise which, as stated above, room surface treatment cannot do. Typical application recommendations are given in the following table.

Table 27.2 *Typical Recommended Acoustical Treatments*

Acoustical Material	*Acoustical Tile*	*Metal-Faced Acoustical Units*	*Acoustical Plaster*	*Sprayed Mineral Asbestos*
Size and Form	Square tiles 12 in. x 12 in.; some up to 48 in. x 96 in. Roof deck 2 ft x 8 ft—thickness most common is $\frac{5}{8}$ in. & $\frac{3}{4}$ in.	12 in. x 24 in. up to 24 in. x 120 in. Thickness is controlled by acoustical pad backing. Either paper-wrapped mineral wool or cut or roll glass fiber. Units run 2 in. to 3 in. total thickness.	A plaster-like material of special fibrous or particulate aggregate $\frac{1}{2}$ in. to $1\frac{1}{2}$ in. thick.	Asbestos fibers sprayed with binder—$\frac{3}{4}$ in. to 3 in. thick.
Surface	Wide variety of perforated, textured, and sculptured surfaces with white, painted, vinyl, and glass cloth finishes.	Baked-enamel finish usually white, but available in color, perforated or slotted.	Fine-grain white texture, but may be spray painted.	Rougher grained than acoustical plaster, has deep texture and can be readily colored.
Method of Installation	Adhesive, nailing, or stapling to wood furring; lay-in grids; concealed spline-grid.	Attached to metal supports nailed to wood furring or hung in a proprietary metal suspension system.	Trowel or spray.	Sprayed on solid surfaces or immediately on metal lath.
Major Area of Application	All interior applications. Check specifications for application in high-humidity areas.	All interior applications. Check specifications for application in high-humidity areas.	Most interior applications. Especially useful for large curved surfaces. Not satisfactory in high humidity.	Architectural and industrial areas where combined fire-proofing and sound absorption are desired or rich texture is required.
Advantages	Provide widest range of finishes in high-absorption units. Mineral fiber tiles are rated incombustible. Lay-in units provide access to plenum above.	Incombustible. Easily maintained. Can be washed or painted; replacement units will match original job. Permits easy access to plenum.	Rapid, low-cost installation on large irregular or curved surface. Fine-grain texture. Incombustible—can be applied with (or as part of) fire protection.	Richly textured surface. Incombustible. Can be included as part of fire-proofing or thermal insulation.
Limitations	Allows transmission of sound over partition in hung ceiling unless selected for high-attenuation factor.	Allows transmission of sound over partition in hung ceiling unless backed by impervious layer.	Easily abused. Difficult to match finish in patching or repairing. Does not always perform as advertised. Performance limited to high-frequency absorption. Dusty in application.	Easily abused. Difficult to match patched areas to original. Dusty in application.

Acoustical Material	*Unit Sound Absorbers*	*Acoustical Form Board*	*Carpeting*	*Drapery*
Size and Form	From 12 in. x 12 in. x 2 in. units to 24 in. x 48 in. plastic coated glass fiber baffles.	Sizes and thickness vary to fit structural requirements (floor and roof slabs only) 1 to $2\frac{1}{2}$ in. for wall application.	Sized or seamed to fit any floor or wall area.	Acoustically transparent fabrics ranging from opaque velours to transparent/translucent glass fibers.
Surface	12 in. x 12 in. units in smooth to rough surface. Baffles are vinyl wrapped.	"Shredded Wheat" or smooth pattern.	Cut, looped, or combination to achieve any degree of "fuzzing."	Velveteen to boucle (rough).
Method of Installation	Units may be applied using special wall clips, pendents (ceiling only), or adhesive. Baffles are wire supported.	According to structural design (floor and roof slabs only). Adhesive or mechanical application on walls.	Tacking (floor only) or adhesive.	According to function and aesthetics.
Major Area of Application	12 in. x 12 in. units are useful in all interior areas. Baffles in industrial areas.	Floor and roof decks wherever applicable. Wall surfaces in most interior spaces.	Floors and walls.	Window or opaque wall areas and room dividers.
Advantages	Permit maximum flexibility. Hung units add sound absorption without requiring lowering lights or sprinkler heads.	Combines form board with thermal insulation and acoustical absorption.	Provides a relative degree of mid- and high-frequency absorption and luxurious appeal.	Provides a relative degree of overall sound absorption and luxurious appeal.
Limitations	Each application must be designed individually.	Not advisable for high-humidity areas.	Acoustical absorption increases with pile height, pad, and fiber density.	Acoustical absorption increases with fabric density percent, fold when drawn, and air space behind.

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SOLID STRUCTURE-BORNE SOUND REDUCTION

REDUCTION OF SOLID-BORNE NOISE

The means of transmission and suppression of Solid-borne sound are considerably different from those of air-borne sound. Solid-borne noise usually originates from impacts or machinery vibration; for example the "hammering" of a water pipe, the dragging of a chair across an uncarpeted floor, or the shaking of an electric refrigerator caused by the unbalance of its motor. Here, the amounts of instantaneous vibratory power involved are tremendous compared with those of the usual sources of air-borne noise. For this reason, and because vibration is communicated through continuous structures with little attenuation, it often is transmitted great distances in a building. Hence, solid-borne noise should be suppressed at its source wherever it is practical to do so.

Measures for accomplishing this include the use of: heavy carpeting, cork tile or linoleum — on — felt to reduce impact transmission to the floor; a segment of flexible metallic or rubber hose, in a pipe to lessen the propagation of impulses along it; flexible mountings for motor and other types of machinery to suppress the communication of vibration to the floor; and a short section of canvas in a ventilation duct to prevent the passage of vibration along the duct.

One vibration is transferred to a solid building structure, such as concrete slab, it travels through the structure with a speed of about ten times that of sound in air. If it reaches a flexible partition, a floor, or a wall, the vibration may force the partition into oscillation, and annoying sounds may then be radiated. The efficiency of radiation depends on the ratio of the dimensions of the partition to the wavelength of the sound (the greater this ratio, the greater the efficiency) and on the internal damping of the partition. For these reasons, a panel that is subject to vibration is sometimes cross-braced to divide it into smaller areas, and damping material (pugging or "dum-dum") may be applied to one side of the panel.

Although massive, rigid partitions (for example, concrete walls) provide effective insulation against air-borne noise, they offer poor protection against solid-borne vibration. On the other hand, porous materials such as blankets, which are relatively poor insulators of air-borne sound, can be used in such a way as to present an effective barrier against the transmission of solid-borne vibration. The most effective type of structure for prevention of propagation of solid-borne noise is that of *"discontinuous construction"* whereby the transmission path is severed or contains marked discontinuities in density and elasticity. This type of construction and other means of protection against solid-borne noise are discussed herein below.

Floors and Ceilings

Well-designed systems must provide adequate insulation against both air-borne and solid-borne noise. A construction that is excellent for one may be poor for the other. For example, a bare concrete slab 1 foot (0.30 m) thick has a high transmission loss for air-borne sound, yet it propagates impacts readily. *Impacts* must be prevented from imparting much energy to a floor of their transmission through the structures is to be suppressed. This can be accomplished by means of a resilient covering such as carpet or cork tile

which will absorb some of the impact. Since the portion of the vibratory energy communicated to the floor will be propagated with little attenuation unless there are structural breaks or discontinuities in the construction, staggered joist construction is superior to ordinary joist construction.

For a floor and ceiling partitions using 2" x 6" to 2" x 8" joists with subflooring and gypsum plaster on metal lath for ceiling the average cycle from 128-4096, the transmission loss TL = 38 for a 2" × 8" at 16" o.c. floor joist with subfloor then a top flooring of wood, one ceiling consisting of ½" plaster on ½" fiberboard lath next to joists; and an additional plaster and fiberboard lath ceiling on 2" × 2" joists suspended by screw eyes and wire loops 36" o.c. 4" below upper ceiling 5" × 5" × 2" fiberboard block pads at fastenings the transmission loss TL = 56.

If a sound level in a room due to a continuous series of impacts on a concrete floor above is 50 db. Then, if carpet on that concrete slab reduces the level of noise in the room to 45 db, the impact-noise reduction is said to be 5 db. The two tables below give the ratings of a number of floor constructions laid on a concrete slab, compared with the rating of the concrete slab itself.

IMPACT-NOISE REDUCTION FOR CONCRETE FLOORS

Impact Noise Transmitted to Room beneath Various Concrete Floor Constructions Compared with That for the Bare Concrete Slab

(R. Lindahl and H. J. Sabine)

Nature of Floor Construction Laid on Concrete	Impact-Noise Reduction in Decibels	Comment of Observer
None (bare concrete)	0	Bad
Asphalt tile (5/32-inch)	0	Nearly as bad
Asphalt saturated felt (1/8-inch)	2	Nearly as bad
Rubber tile (3/16-inch)	7	Better than concrete
Heavy carpet (no pad)	10	Good
Linoleum (3/16-inch) on felt	12	As good as carpet
Asphalt-saturated fiberboard (1/2-inch)	12	As good as carpet
Hardboard (3/16-inch) over fiberboard (1/4-inch)	17	Better than carpet
Wood floor (3/4-inch) on sleepers (2-inch by 3-inch)	19	Very quiet
Cork tile (1/2-inch)	20	Very quiet
Wood floor (3/4-inch) on sleepers (2-inch by 3-inch)	19	Very quiet
Cork tile (1/2-inch)	20	Very quiet
Wood floor (3/4-inch) on sleepers (2-inch by 3-inch), rock-wool fill	20	About same as construction without rock wool

IMPACT-NOISE REDUCTION FOR CONCRETE FLOORS

Impact Noise Transmitted to Room beneath Various Concrete Floor Constructions Compared with That for the Bare Concrete Slab

(Building Research Station at Garston)

Nature of Floor Construction Laid on Concrete Slab	Impact-Noise Reduction in Decibels *
None (bare concrete)	0
Carpets, etc.:	
Linoleum (1/8-inch) and linoleum (1/8-inch) on roofing felt	5
Wood blocks, thin carpet, rubber	5-10
Carpet (1/8-inch) on underfelt (1/8-inch), hard rubber-cork composition (¼-inch)	10
Sheet rubber (1/16-inch) on sponge rubber (¼-inch)	20
Screeds (concrete slab), 2-inch, on following underlays:	
Clinker	5-10
Granulated cork (1-inch)	10-15
Slag-wool quilt or eelgrass quilt	15-20
Glass-silk quilt, single-layer, or eelgrass quilt, double-layer	20
Glass-silk quilt, double-layer	25
Boarding on battens on following underlays:	
Clips	5-10
Asbestos pads or felt pads (½-inch)	5-10
Fiberboard pads (½-inch)	10
Felt pads (1-inch) or rubber pads (½-inch)	10-15
Eelgrass quilt or slag-wool quilt (½-inch)	10-20
Glass-silk quilt or rubber pads (½-inch)	15-20
Suspended ceilings:	
Plaster (¼-inch) on fiberboard (½-inch) on battens in clips (2-inch by 2-inch)	5-10
Plaster (3/8-inch) on plasterboard (3/8-inch) on battens in felt-lined clips	10-15

* Frequency-weighted sound-pressure level, averaged to the nearest 5 db.

In table (c) is given the impact-noise reduction for wood floors; a normal board and joist floor, together with a lath and plaster ceiling, is used as a basis of comparison. The addition of 20 pounds per square foot of sand or ashes improves the impact-noise reduction by 10 db. The reason is that the whole floor being of light weight, tends to vibrate under impact. Increasing the mass of the structure reduces this tendency. The added material also increases the damping of the structure.

IMPACT-NOISE REDUCTION FOR WOOD JOIST CONSTRUCTION

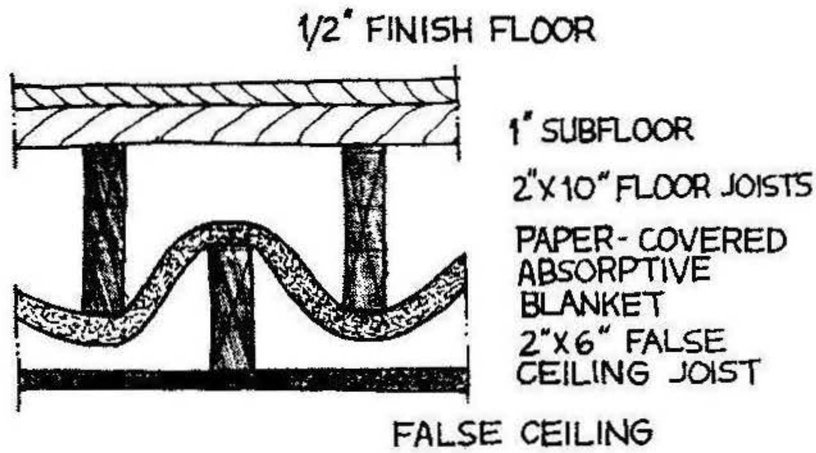
Impact Noise Transmitted to Room beneath Various Wood Floor Construction Compared with That for an Ordinary Board and Joist Floor, Lath and Plaster Ceiling

(Building Research Station at Garston)

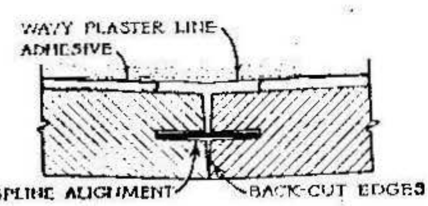
Nature of Floor Construction	Impact-Noise Reduction in Decibels *
Normal board and joist floor, lath and plaster ceiling	0
Plaster on plaster board ceiling	0
Pugging (sand or ashes, 10 lb per sq ft, or slag wool, 2 lb per sq ft)	5
Separate joists to carry ceiling	5
Floor boards on cross battens on glass-silk quilt, not nailed	5
Floor boards on fiberboard, on sub-boarding	5
Floor boards on glass-silk quilt, on sub-boarding	10
Sand or ashes, 20 lb per sq ft	10
Carpet on underfelt	10

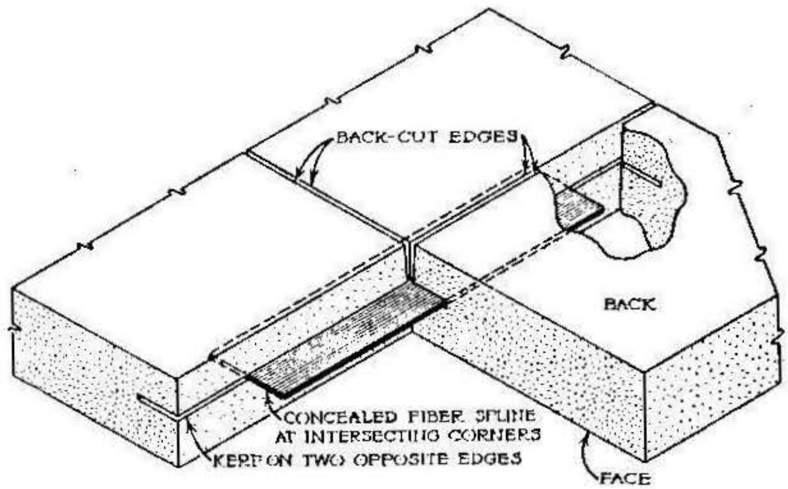
* Frequency-weighted sound-pressure level, averaged to the nearest 5 db.

If good isolation against impacts is to be obtained, the ceiling should not be rigidly connected to the floor joists. If the ceiling is carried independent joists, as in the figure below, the impact-noise reduction



will be improved by at least 5 db. (The principal benefit of the addition of a paper covered absorptive blanket, as shown, is in the reduction of air-borne sounds). Resilient clips provide a convenient means for attaining good isolation between a ceiling and the structural floor from which it is hung. A method for suspending acoustical tile ceilings is illustrated on the next page. Similar methods are effective also for suspending ordinary lath and plaster ceilings.



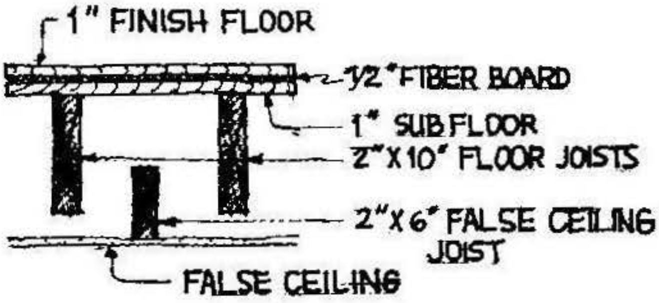


Consideration must be given to the floor surface in the acoustical design of a floor construction. It is frequently important to choose a wearing surface such that impacts against it will be muffled and this will generate little noise in the room where they are produced. The benefits resulting from the use of carpeting in the aisles and lobby of an auditorium have already been stressed in the chapter VI (Acoustical design of rooms). The "Relative Noisiness" values of a number of floor surfaces are listed in the table below.

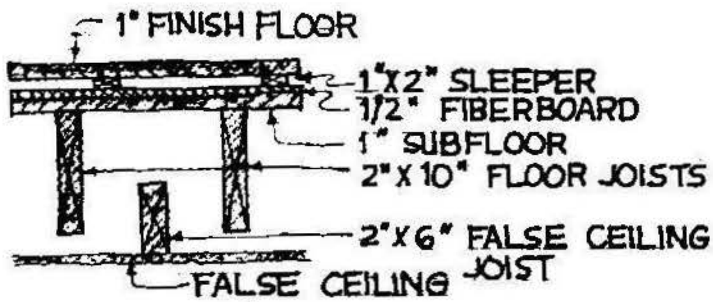
Age Group	Loss in Decibels		
	Frequency		
	880 cycles	1760 cycles	3520 cycles
10-19			
Men	0.6	0.6	1.8
Women	0.6	0.4	0.3
20-29			
Men	0.1	0.3	2.7
Women	0.4	0.3	0.7
30-39			
Men	0.3	0.6	6.0
Women	1.2	0.8	1.6
40-49			
Men	1.4	2.6	16.0
Women	2.1	1.5	3.0
50-59			
Men	2.6	6.0	27.0
Women	4.0	4.0	7.0

1. FLOATING FLOORS

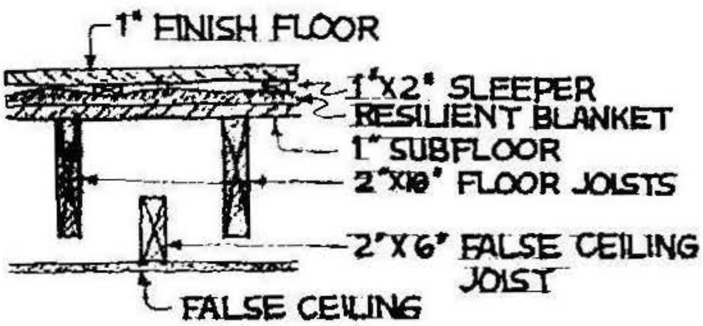
The isolation provided by a floor system against mechanical impact can be greatly improved by the use of a "floating" floor which rests on the structural floor but is separated from it by a resilient support or quilt, as in the following figures below.



(a)



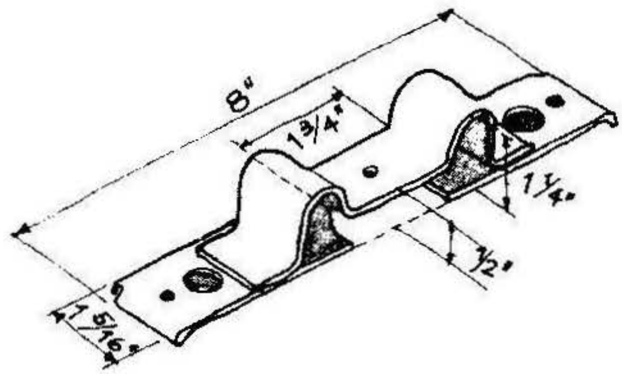
(b)



(c)

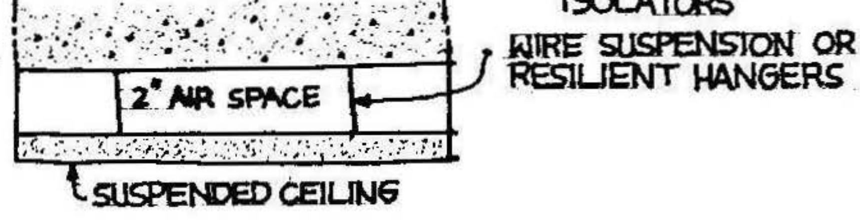
Not only is the impact — noise reduction improved by such floating floors, but also the transmission loss for air-borne sound is increased slightly, In choosing a resilient support for a floating floor, one must consider the safe amount of loading the support can withstand without being compressed to the extent that its resilience is practically lost. In general, the most satisfactory materials are very resilient ("springy"), and they return to their initial condition when the load is removed. Slab cork, granulated cork, rubber, fiberboard, felt, wood-wool and certain types of mineral-wool blankets are among the available materials that meet these requirements.

Flexible steel supports and clips are less subject to defects. The effectiveness of a floating floor system is dependent on the extent of isolation provided by the resilient supports between the floated finish floor and structural floor. Care should be taken that this isolation is not "shorted" by nails or by solid connections anywhere-including the functions between the floating floor and the walls. Thus in the figure (c) p. 181 a resilient blanket is laid on a sub-floor; the finish floor is nailed to sleepers which rest on the blanket. The sleepers must not be rigidly connected to the subfloor; they should float on the blanket or be fastened by resilient chairs. see figure.



The blanket should have a paper, or similar, covering on at least one side to improve the insulation against air-borne sounds.

For isolation of heavy impacts. wood floor constructions are very poor. Since they are relatively light, the whole floor easily can be set into vibration. The floor construction shown in the figure below is a superior one. For example, a resilient quilt is laid on a concrete supporting floor; a concrete slab 2 inches thick is then poured directly on the blanket.

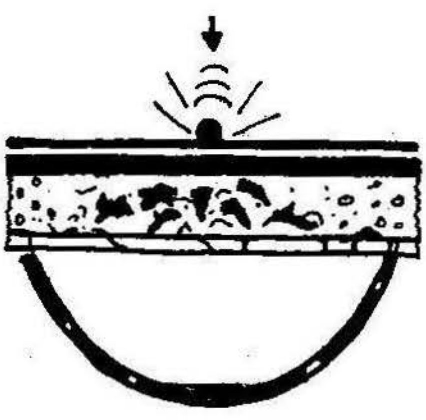


Control of Impact Noise

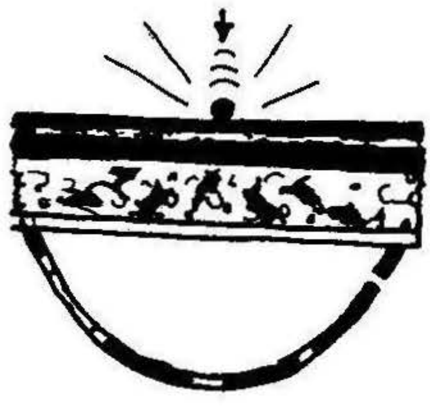
Impact noise problems can be controlled in two ways.

(1) By preventing or minimizing the impact, and

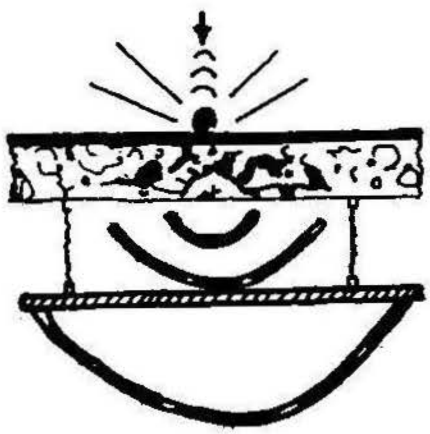
(2) By attenuating it once it has occured.



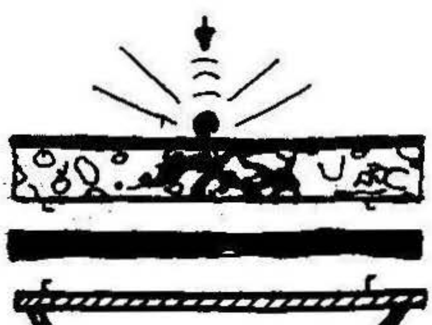
A. CUSHION IMPACT



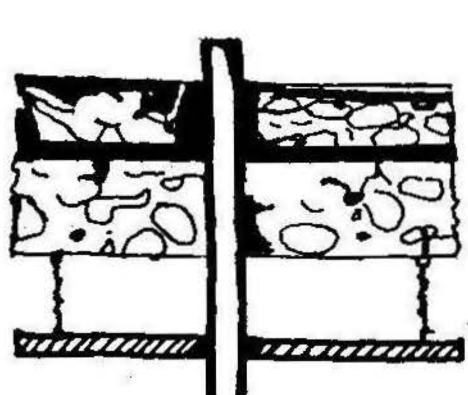
B. FLOAT FLOOR



C. SUSPEND CEILING



D. SOUND ABSORBER IN CAVITY



E. ISOLATE AND SEAL PIPING, ETC.

(a) **Cushion the Impact**

This obvious solution will frequently eliminate all but severe problems. The resilient materials in common use are floor tiles of vinyl, cork, rubber, or carpeting on pads.

(b) **Float the Floor**

Since the key to elimination of structure-borne sound is isolation, separating the impacted floor from the structural floor by a resilient element is extremely effective. This element can be rubber or mineral wool pads, or blankets or special spring metal sleepers. Its effectiveness depends on the mass of the floating floor, compliance of the resilient support, and degree of isolation of the floating floor. This last element is extremely important, since flanking paths via end contacts with walls can short-circuit the floating elements sound impedance and defeat the system. With floating floors it is important that:

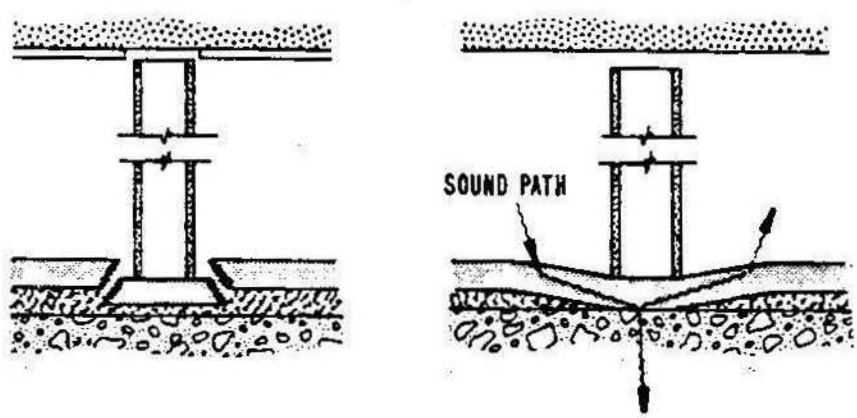
1. Mass of the floating floor be large enough to properly spread the loads. Otherwise, the pad will compress and deform sufficiently to transmit the impact.

2. Total construction must be airtight. Airtight is soundtight.

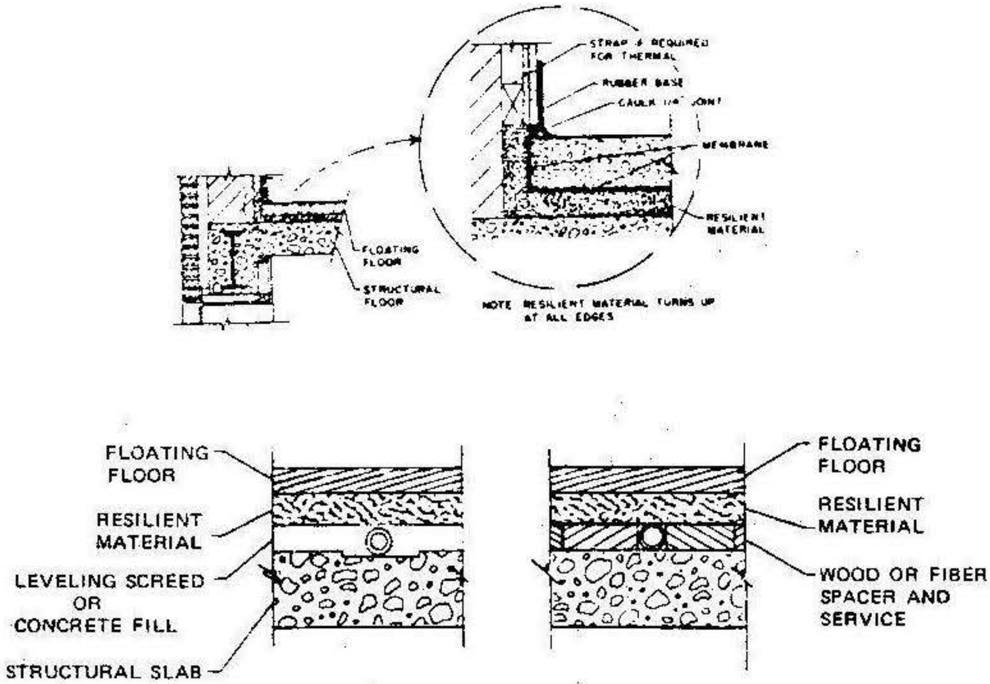
3. Particular care be exercised where partitions rest on the floating floor.

Caution must be exercised when supporting partitions on floating floors to prevent structural failures or short circuiting of the floating element, as illustrated.

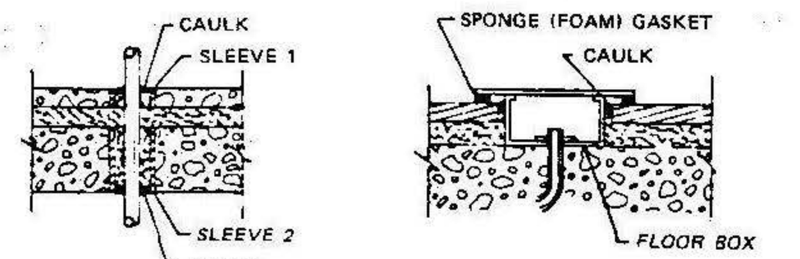
For proper installation of floating floors and partition walls see other illustrations of such constructions in this chapter.



4. Short circuits at walls or by penetrations be avoided.



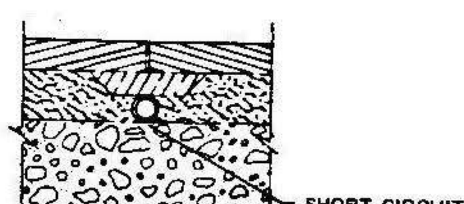
(a)



TWO SLEEVES ARE REQUIRED TO PASS PIPE, ETC. THROUGH FLOATING FLOOR

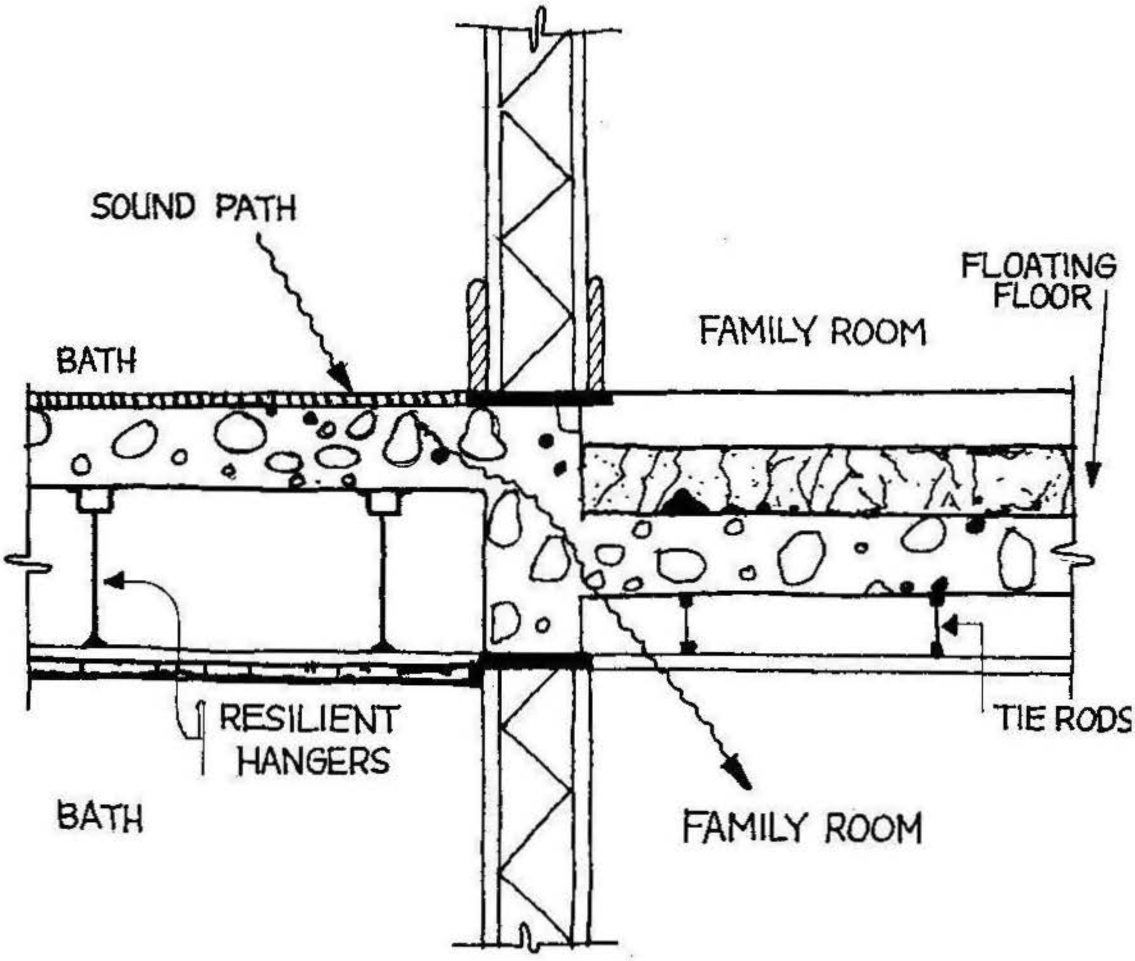
PENETRATIONS OF FLOATING FLOORS MUST NOT "SHORT OUT" THE RESILIENT LAYER

(b)



(c)

5. Construction throughout must be consistent. Mixed-construction types invite flanking noise paths.



(c) **Suspend the Ceiling — and use Absorber in Cavity**

As stated, the most disturbing noise is radiated down from the ceiling. A flexibly suspended ceiling with an acoustic absorbent layer suspended in it can be very effective if not flanked by paths leading into the walls and from there reradiating into the space below. It is imperative that the entire floor slab above be decoupled from the walls below by resilient separators.

(d) **Isolate all Piping**

All rigid structures such as piping must be isolated so as not to form a flanking path, and caulked with resilient sealing so as not to constitute an air-sound leak. (see last fig. above)

Mechanical System Noise Control

Mechanical Noise Sources

Mechanical devices obviously make noise. And, generally, the more power they consume the more noise they make. In many of today's buildings, 40% of the total cost is spent on mechanical systems. These systems are located throughout a building.

In most buildings, the primary sources of mechanical noise are the components of the air-conditioning and air handling systems such as fans, compressors, cooling towers, condensers, ductwork, dampers, mixing boxes, induction units, and diffusers.

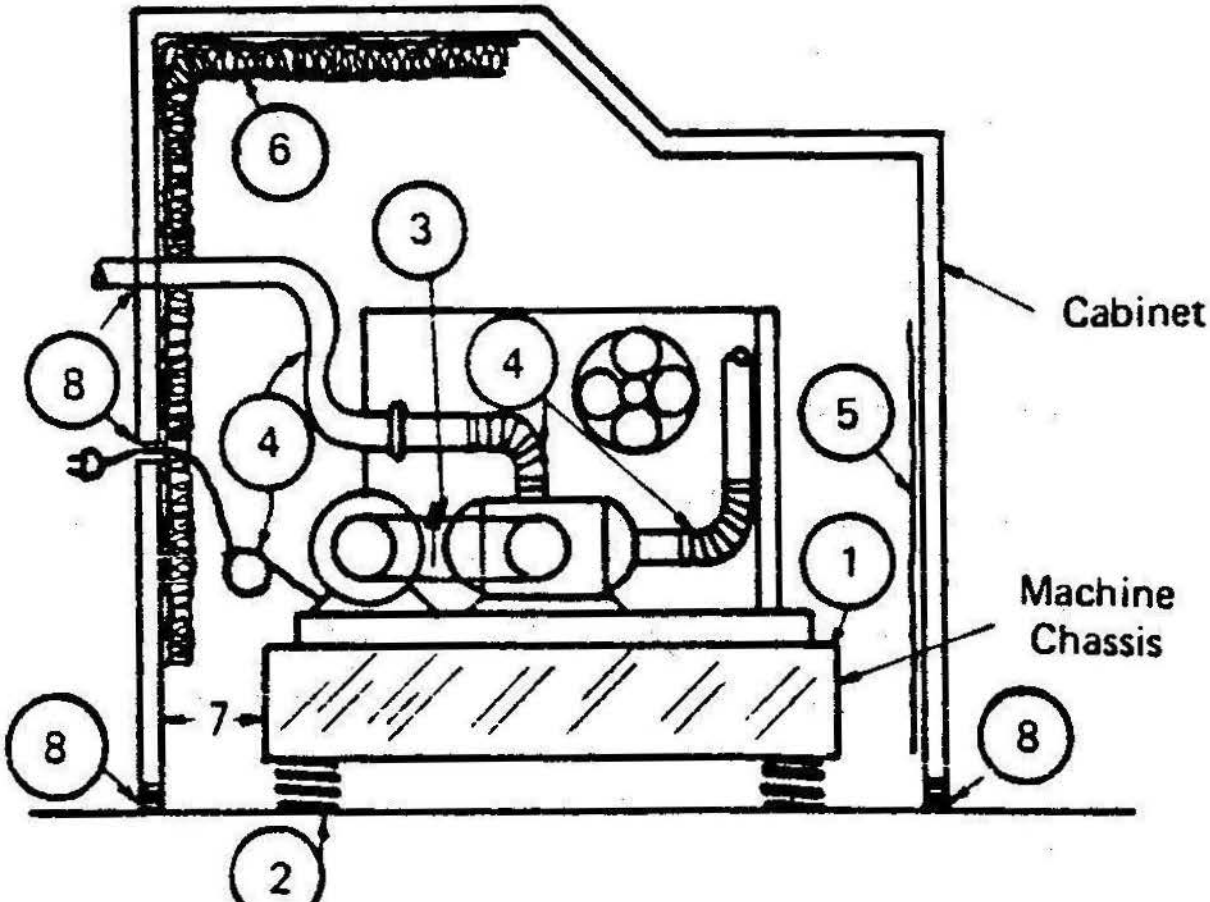
Pumps are another source of mechanical noise. Pump noise is frequently transmitted along pipes to remote points. Pumps for water-pressure boost systems may be located outside of mechanical rooms and be overlooked until problems occur in the completed building.

Elevators, escalators, and freight elevators also introduce mechanical noise into the building. Escalators and freight elevators pose few problems, since they are localized in a specific area and have low operation speeds. However, elevator-car operation is rapid and it affects large areas. In addition, the motors and switchgear are located on or above the prime upper floors of a building. Motor, shaftway, and switching noise must be properly controlled to prevent annoyance to building tenants located near the shaftways or mechanical penthouses. Vibration isolation of these major components is a specialized problem.

Quieting of Machines

Machines cause noise by vibration. This noise is imparted directly to the surrounding air and by vibrational contact to the surrounding structure. Therefore, there are three ways to reduce this noise:

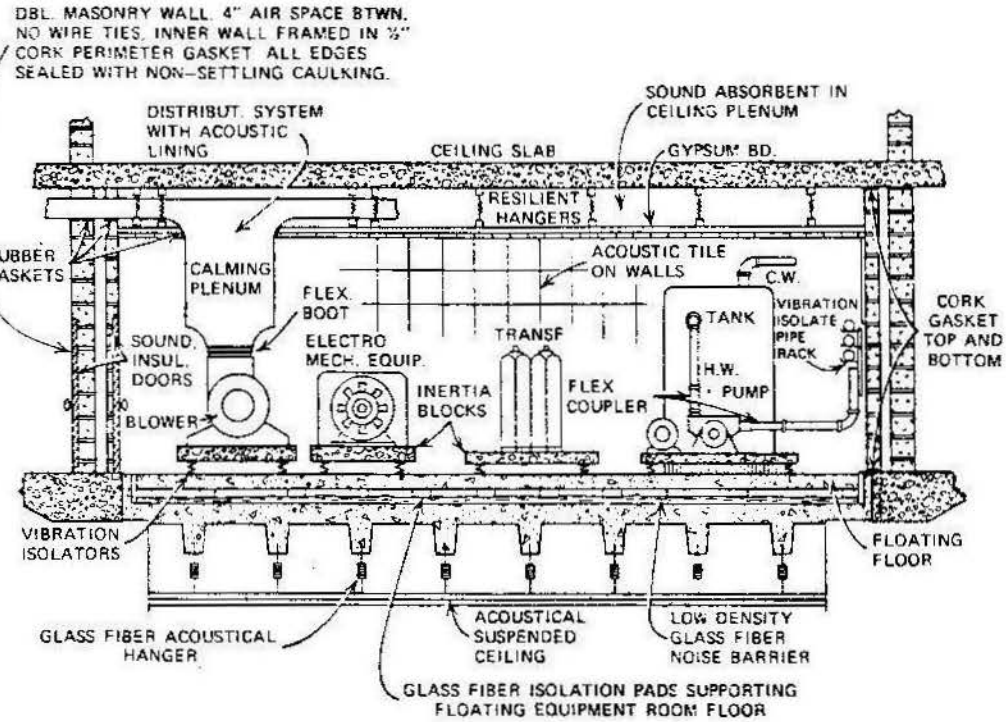
(a) Reduce the vibration itself.
(b) Reduce the air-borne noise by decoupling the vibration from efficient radiating sources.
(c) Decouple the vibrating source from the structure.



1. Install motors, pumps, fans, etc. on most massive part of the machine.
2. Install such components on resilient mounts or vibration isolators.
3. Use belt drive or roller drive systems in place of gear trains.
4. Use flexible hoses and wiring instead of rigid piping and stiff wiring.
5. Apply vibration damping materials to surfaces undergoing most vibration.
6. Install acoustical lining to reduce noise buildup inside machine.
7. Minimize mechanical contact between the cabinet and the machine chassis.
8. Seal openings at the base and other parts of the cabinet to prevent noise leakage.

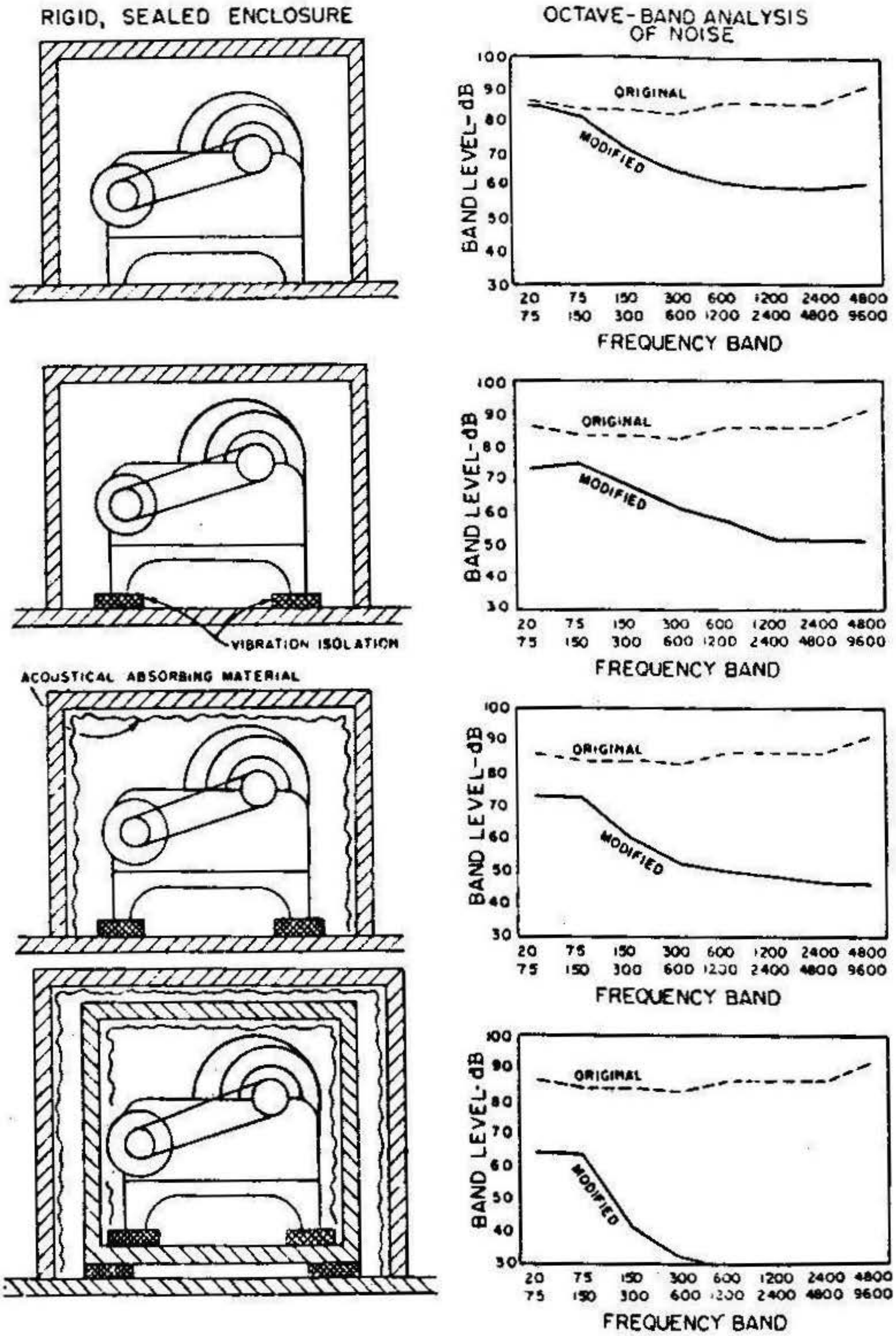
Referring to the figure above, items 1, 3, and 4 reduce vibration; items 4,5,6, and 7 reduce and decouple the vibration from the radiating cabinet and items 2 and 8 decouple the vibrating source from the structure.

VIBRATION REDUCTION takes two forms, damping and isolation. DAMPING is accomplished by rigidly coupling the vibrating source to a large mass, frequently called an inertia block. Much of the energy is absorbed and dissipated as friction; the ramainder results in lower-amplitude vibration. See figure below



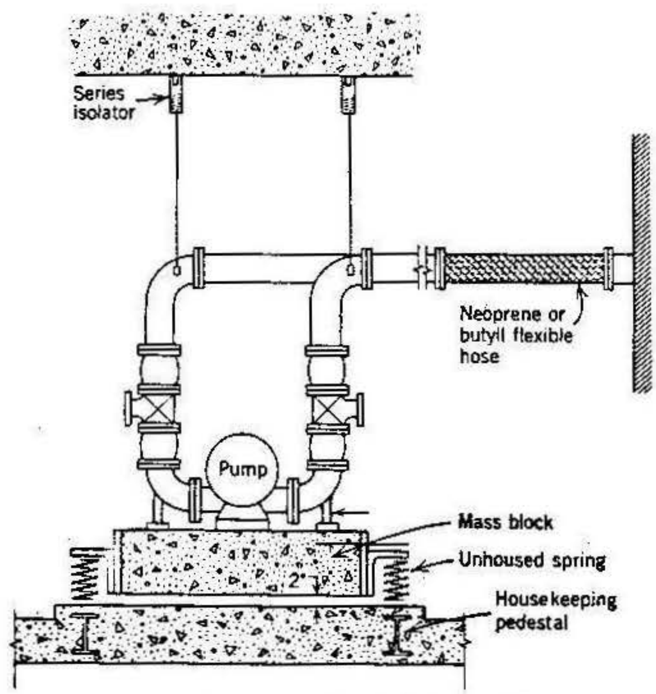
ISOLATION is accomplished by supporting the vibrating mass on resilient supports. These take many forms and are used in tandem. Thus, machines are supported on fibrous rubber, or spring steel vibration isolators, and the entire mass can be supported on a floating floor, which in return rests on resilient vibration isolators as in the above figure. Large machines are supported as special commercial "sandwiches" of asbestos, lead, cork, and other strong resilient materials. Piping is supported on cork pads and hung on resilient hangers. Machines with a dominant vibrational frequency can have special springs designed to give maximum isolation and damping at that frequency. Massive machines and impacting devices use huge inertia blocks and even separate foundations to isolate their vibration.

The recent emphasis on emergency electric generators has caused a serious noise and vibration problem due to the large mass and extremely high noise levels. For such units complete enclosures are frequently the best approach. (see figure below) Flexible joints in all pipes and ducts connected to vibrating machines and mandatory. This includes flexible conduit connectors to all motors, transformers, and lighting fixtures using ballasts.



The important aspect of this illustration is that each of the individual sound attenuation techniques is insufficient of itself, and only a combination of isolation and absorption will perform the requisite quieting. The last step—double isolation—is only required with very high noise levels or every low background noise requirements.

PUMPS, as with all rotating equipment are sources of vibration and noise and should be treated as described above. The figure below shows a typical pump installation with appropriate noise reduction measures. For at least a distance of 100 pipe diameters beyond the pump resilient pipe hangers should be used. With centrifugal pumps as with fan and blowers, machine sound concentrates in narrow bands and, if extremely disturbing, can be attenuated with resonant filters. Reciprocating pumps are more difficult to control as the pulsations are more vibration than noise. Flexible connections in the piping and U-joints in the piping will absorb much of this vibration.

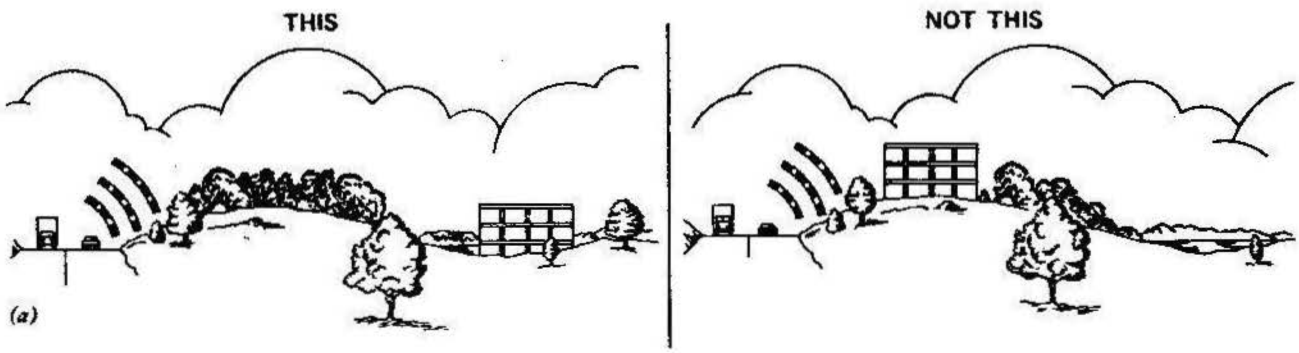


Typical pump installation with appropriate isolation and damping measures.

Building Siting

As important as interior structural design is building siting vis-a-vis exterior noise sources. Buildings should be sited, with respect to noise sources:

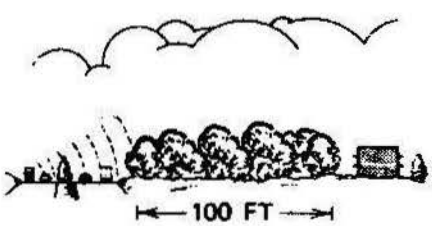
(a) To use natural terrain noise barriers.



(a)

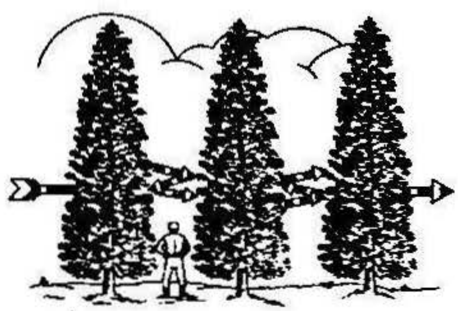
(b) With respect to trees as noise barriers, rely only on thick wooded areas.

(b)



A THICK GROWTH OF LEAFY TREES AND UNDERBRUSH REDUCES NOISE ABOUT 6 to 7 DB/100 FT (AVERAGE OVER AUDIBLE FREQ. RANGE)

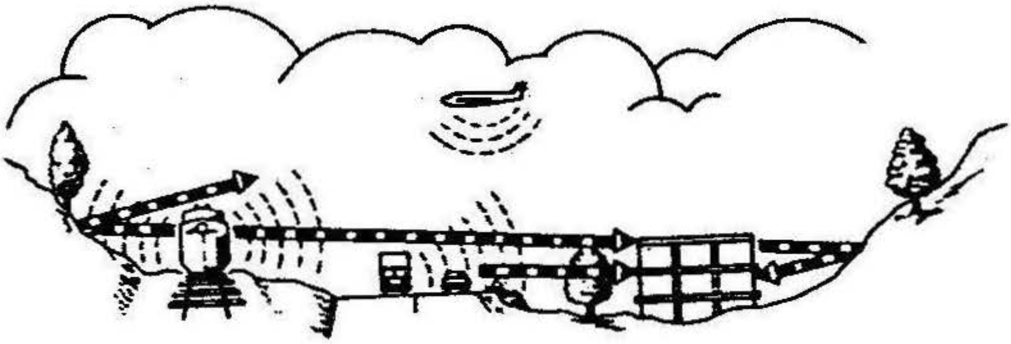
LOW–FREQ. LOSS: 3–4 dB
HIGH–FREQ. LOSS: 10–12 dB



HIGH FREQ. REDUCTION 3–4 dB

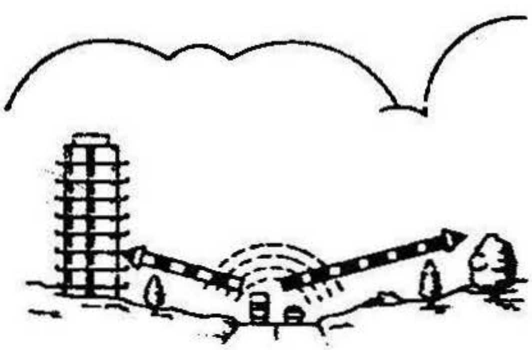
SINGLE ROW OF TREES IS WORTHLESS AS NOISE BARRIER. DUE TO INTER–REFLECTION MULTI–ROWS OF TREES ARE MORE EFFECTIVE

(c) To avoid naturally poor sites

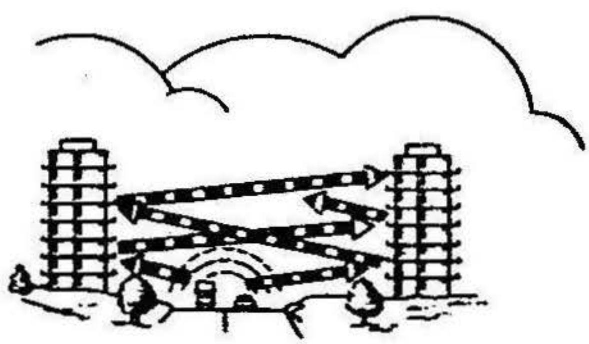


AVOID HOLLOWS OR DEPRESSIONS.
THEY ARE GENERALLY NOISIER THAN
FLAT OPEN LAND.

(d) To avoid sound reflection from other builbings.



BUILDING SITES IN OPEN
AREAS ARE LESS NOISY
THAN SITES IN CONGESTED
BUILDING AREAS

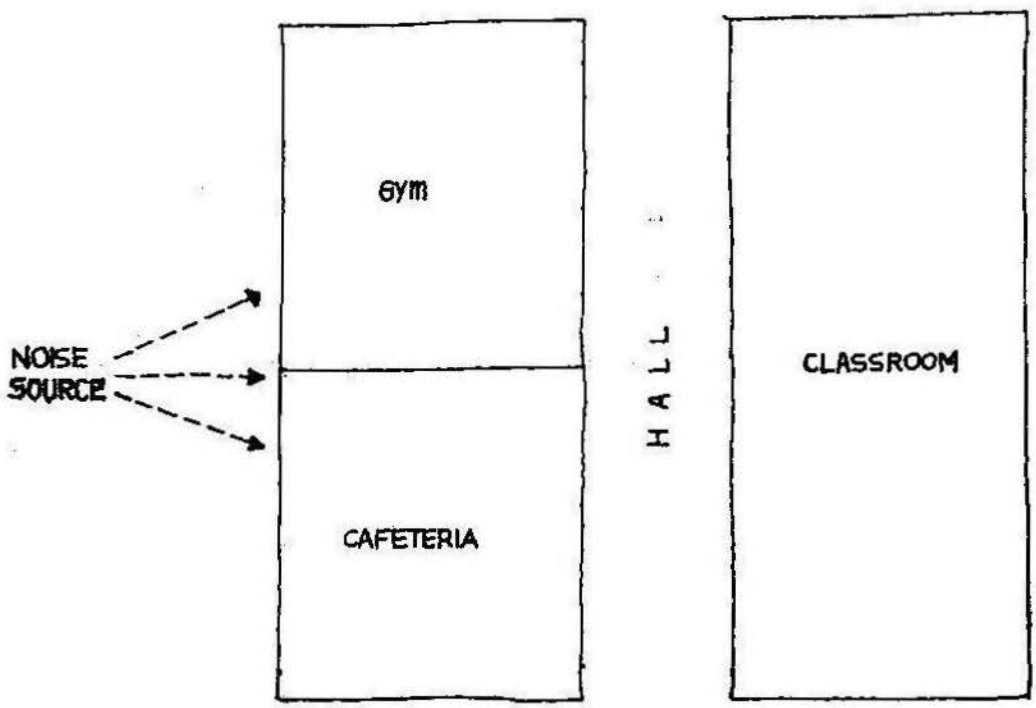


TRAFFIC ARTERIES BETWEEN
TALL BUILDINGS ARE
QUITE NOISY.

factor (d) is also important in a multiwing building; in avoiding U-shapes or other configurations where a central court becomes an echo chamber.

Room Arrangement

Where avoidance of an exterior noise source is impossible, quiet zones can be buffered from the noise by placing higher-noise areas on the noisy side of the building. Thus. in a school, classrooms and offices can be buffered by a cafeteria and gym. In a residence bedrooms by living rooms and corridors, in an office building, private offices by noisier clerical offices and so on.

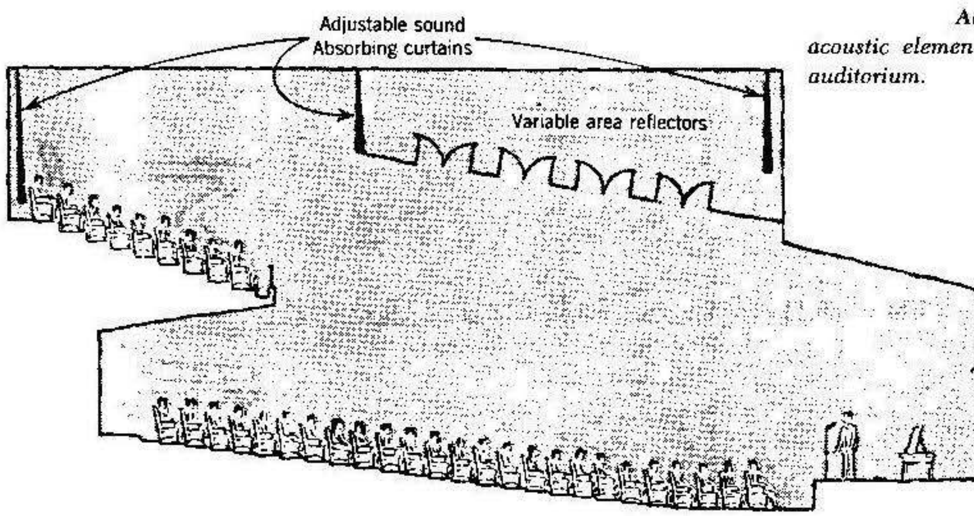


11

AUDITORIUM ACOUSTICS

AUDITORIUM DESIGN

This is a general term used to describe a space where people sit and listen to speech or music. A large lecture hall, a multipurpose space, and a concert hall are auditoriums. (Sometimes they call a gymnasium being used as an auditorium a GYMNATORIUM). Before beginning design of an auditorium, its potential use must be determined. If planned activities range from lectures to symphony orchestra concerts, the design approach for acoustics will differ, significantly, from a design approach for a space that would house only one of these activities. Therefore, the first step in the acoustical and architectural design must be determining the program. If the program for the auditorium includes activities that need different acoustical environments, it must be decided early whether the acoustics will be a compromise between the program extremes or adjustable for various activities. Acoustical environments can be altered by changing volume, moving reflecting surfaces, and adding or subtracting sound absorbing treatment.

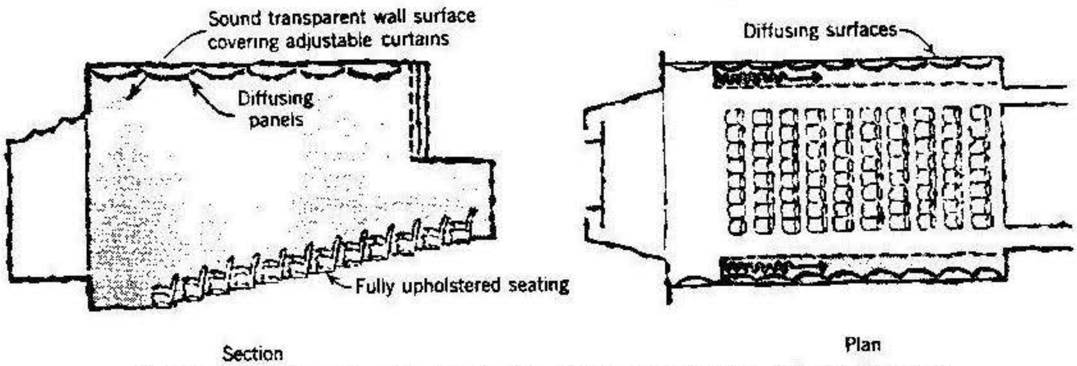


Adjustable acoustic elements in an auditorium.

FACTORS that influence the acoustical design include audience size, range of performance activities, and sophistication of the potential audience. Obviously, an acoustical good 1200-seat theater is more difficult to design than an acoustically good 400-seat theater. In addition, the caliber of performance production and audience expectations are important design considerations. For example, a small school auditorium and a professional theater will have widely divergent demands from both audience and performers.

Acoustical design of an auditorium includes room acoustics, noise control, and sound system design.

The audience size determines the basic floor area of an auditorium. Once this area has been fixed, the volume of the room is developed according to reverberation requirements of the space.



Auditorium with surface treatments for control of reflections and reverberation.

The figure above shows a typical auditorium in plan and section. The shape of wall and ceiling surface is developed to give proper distribution of sound and eliminate focusing or echoes. Essential characteristics of the design include:

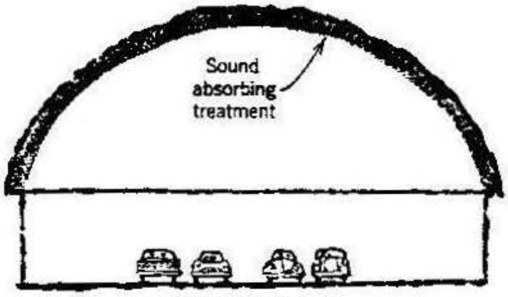
1. Ceiling and side walls at the front of the auditorium distribute sound to the audience. These surfaces must be close enough to the performers to minimize time delay between natural sound and reflecting sound.
2. Ceiling and side walls provide diffusion.

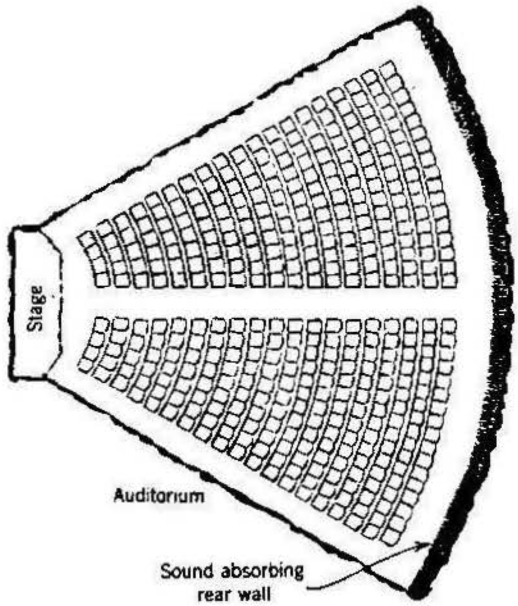
Acoustics must be considered in selection of materials used in an auditorium. Both sound-reflecting and sound absorbing materials will be found in all auditoriums. Since the largest area of sound-absorbing material in any auditorium is the audience, the difference in acoustical characteristics that occur without an audience may be minimized by using fully upholstered seating.

Chairs with fully upholstered seats and backs, covered in an open-weave material, will have absorption characteristics closely approximating an audience. Using the auditorium in the above figure as an example, the reverberation characteristics of an auditorium with various materials may be examined. In the *(first)* example, the room use is assumed to be for music performance. The only sound absorption is that provided by the audience and seating. In the *(second)* set of calculations absorptive curtains were installed along the rear wall and a portion of the side wall. This configuration might be used for lectures in a room that is adjustable between speech and music configuration. A *(third)* configuration might use permanent sound-absorbing treatment installed on the ceiling and rear and side walls. Because of its low reverberation time. This configuration would be appropriate only for movies and lectures, not for music activities.

These simple examples indicate the effect of changes in the amount of absorption on the characteristics of a room. Adjustable treatments permit the characteristics of the room to be modified to any point between the extremes to meet the program acoustic requirements of a multipurpose hall.

Existing spaces may require remedial treatment to eliminate unwanted phenomena such as focusing and echoes, as shown in the figure below.





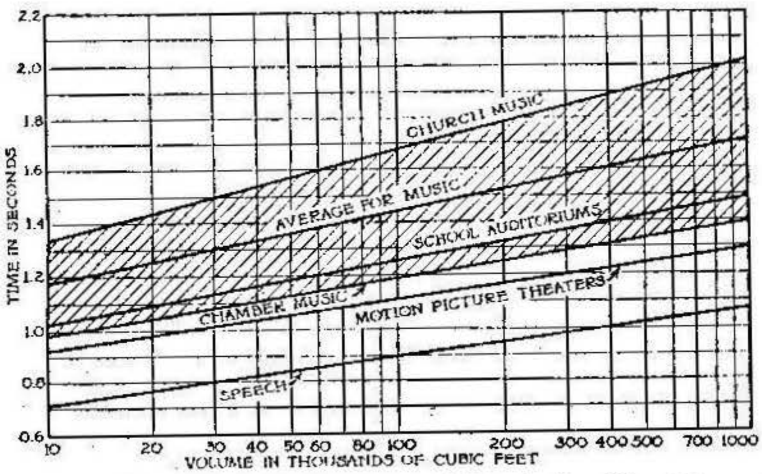
Sound-absorbing treatment used to eliminate focusing from dome and curved auditorium wall.

In the first example, the surface of the dome was covered with sound-absorbing material to eliminate focusing; in the second sound-absorbing treatment was applied to a curved rear wall to eliminate an echo. Such treatment also will affect the reverberation characteristics.

PLANNING THE AUDITORIUM

In working out the acoustical plans for an auditorium, the Architect should take the steps enumerated in the first part of chapter IV (Acoustical Design of Room). Specifically, these four steps are necessary:

1. Examine the site with respect to *noise*. The information gained from a study of existing and prospective sources of noise in the neighborhood of the site is necessary to determine the nature of sound insulation that must be incorporated in the building to prevent the noise level in the finished auditorium from exceeding the maximum tolerable level — 30 to 40 db. It is also necessary to reduce noises originating within the building so that the composite noise level all sources does not exceed the appropriate tolerable level.
2. Limit the *size* of the auditorium.
3. Design the *shape* of the auditorium in accordance with principles described in chapter VI (Design of Room Shapes), so that the plentiful flow of direct and beneficially reflected sound will reach all auditors, and so that the audience area will be free from echoes, flutters, and sound foci.
4. Provide the *Optimum reverberation* in all parts of the auditorium throughout the range of frequencies that are important for speech and music. The curves of the figures next page should be used for determining the optimum reverberation time versus frequency characteristics,



Optimum reverberation time at 512 cycles for different types of rooms as a function of room volume.

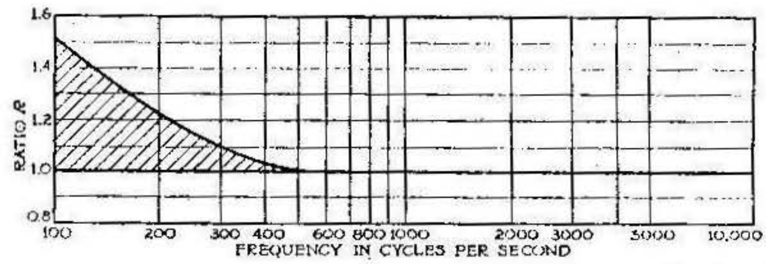


Chart for computing optimum reverberation time as a function of frequency. The time at frequency f is given in terms of a ratio R which should be multiplied by the optimum time at 512 cycles, as given by to obtain the optimum time at frequency f.

THE LITTLE THEATER

In the little theater the architect has an opportunity to design a structure that will embody the highest attainable standards of acoustics. If the seating capacity is limited to 300, the volume of the auditorium should not exceed 50,000 cubic feet (1,800 cu. m.) 10.00 × 18.00 × 10.00. All seats are located on one floor, the rear portion of which should have a steep slope so that auditors will have good sight lines and good sound lines in all parts of the auditorium.

The ceiling should not be more than 6.00 m. high and should be left smooth. A material with a highly reflective finish will serve to direct the sound toward the rear seats. Diverging walls are desirable but not so necessary as in larger theaters. The lower 1.80 m. to 2.40 m. of the side walls should be of reflective material. The front portion of these walls should not be pierced with boxes.

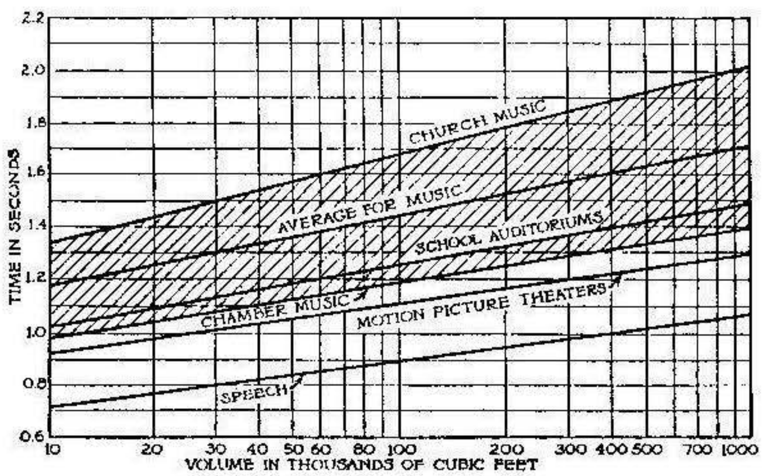
The rear wall should *not be concave.* If this wall is probable source of echoes or interfering reflection (as it may be if it is far enough from the stage), it should be treated with highly absorptive material and broken with deeply inset doors, hangings or other ornaments that will minimize the effects of long delayed reflections and will facilitate proper diffusion. If additional acoustical treatment is required to impart to the room the optimum reverberation characteristic, It should be applied to the upper portion of the side walls in non-uniform strips, or patches.

The chairs should be upholstered with absorptive cloth, such as mohair, over deep porous padding. The absorption of each chair should be 3 to 4 square-foot units (sabins). .60 × .60 m. at all frequencies above 512 cycles, and 2 to 3 sabins at frequencies of 128 and 256 cycles. The reverberation time of the theater will then be rearly independent of the size of the audience. Even during rehearsals the reverberation will be close to the optimum value.

The benefits associated with the small volume (less than 50,000 cubic feet for the audience space) should not be nullified by making the stage recess so large that the sound so is dissipated before it reaches the seating area. The volume of the stage should be reduced to a minimum consisted with other requirements. Stage settings with rear, side, and overhead reflective surfaces should be designed to confine the sound to a small volume and reflect it to the audience. The use of plywood flats or heavily painted and back-painted canvas flats is advantageous for the ceiling as well as for the side and rear walls of the stage set..Designers of stage sets should be instructed to recognize these pertinent requirements for good acoustics, which are especially necessary when the stage is large.

The stage floor should be elevated as much as possible, but it should provide also good sight lines from all seats; this usually will allow an elevation of about 42 inches above the front level portion of the main floor. Orchestra pits should be avoided whenever possible; if indespensable, it is advisable that they be covered with a sound-reflective apron (plywood or heavily painted canvas) when not in use.

The optimum times of reverberation for the auditorium in a little theater with a volume of about 40,000 cu. ft. (the volume of stage not included) are approximately 1.5 seconds at 128 cycles, and 1.0 second at 512 to 4096 cycles. These values are a compromise between those given by the curves for "speech" and "average music" as shown in the figure below.



The exclusion of both outside and interior noise should study whether the site is quiet or noisy. The average level of noise in the unoccupied auditorium should not exceed 35 db, and if highest standards of acoustics are required this level should be reduced to 30 db. This reduction will necessitate considerations of noise conditions at the site and calcula-

tions of sound insulation such as have been described in chapter 9. Suitable wall and ceiling structures and entrance and exit doors must be chosen to provide adequate protection against outside noise. Corridors, promenades, lobbies, and vestibules should be interposed between the auditorium and probable sources of outside or indoor noise. These interposed spaces should be treated with highly absorptive material, not to reduce outside noise but also to exclude the possibility of feedback of reverberant sound from these "coupled spaces" to the auditorium. About one half of the wall and ceiling surfaces should be covered with highly absorbent materials, and the floors should be carpeted over heavy felt pads.

The combined effects of this noise-reduction measures should reduce the average noise level in the theater to 35 db. Thus, if the outside noise transmitted into the auditorium has a level of 32 db, the noise from inside origin-such as that from the ventilating and other equipment, and from diverse activities in the building-must not have a level of more than 32 db so that the level of the combined noise, from ouside and inside, will not exceed 35 db.

This figure show that, when two "random" noises of the same level are added, the combined noise level is 3 db greater than the level of either component.

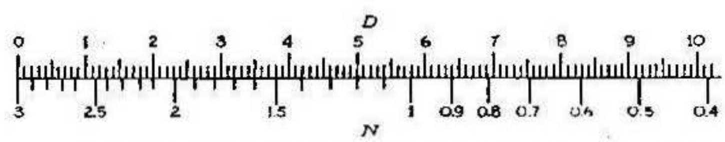
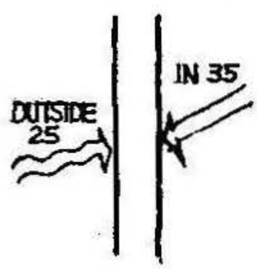


Chart for computing the sound level resulting from the addition of two combining random noises. If D is their difference in decibels, N is added to the higher level to obtain the total level.

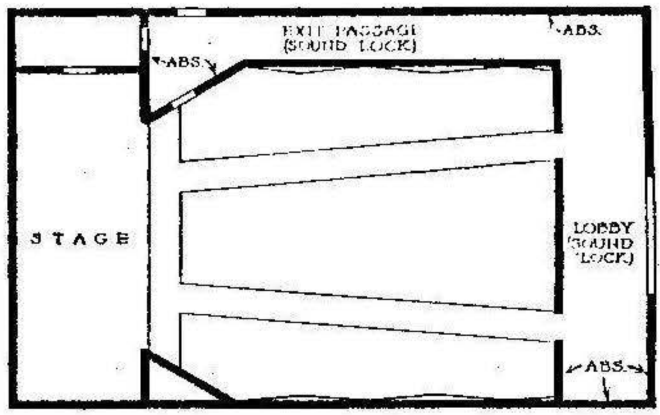
ex. Suppose that the average background sound level in a legitimate theater due to audience noise is 35 db. Assume that the noise transmitted through the walls of the building from outside has a level of 25 db (difference D = 10 db). Below the figure under 10 is 0.4. So, 35 to 0.4 (the higher level plus the N).

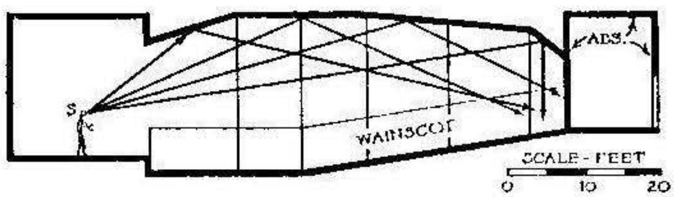


DIFF of 35 and 25 = 10
see N below 10 = 0.4
add to higher level

A noise level of 35 db will not be noticed by an audience except during intervals of unusual dramatic suspense; for example, when the audience listens in rapt silence to a faint whisper.

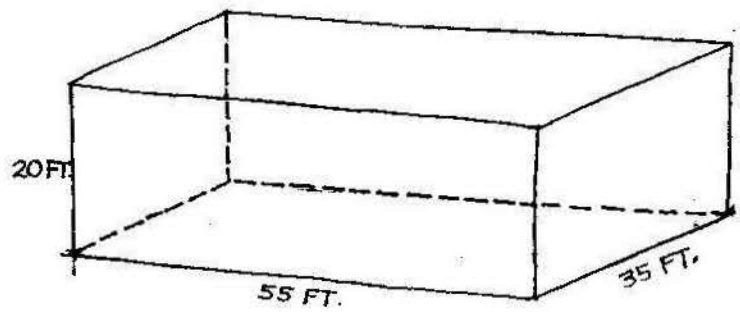
A sketch of a plan and section for a little theater, based on a study of the requirements for ideal acoustics, is shown in the figure below.





The auditorium is isolated by two walls on the sides that are adjacent to streets. These walls, in combination with the promenade and lobby which they enclose (and which, with heavily carpeted floors, act as sound locks), provide an average transmission loss of at least 60 db. This amount of insulation is sufficient to exclude all ordinary sounds, even in a noisy metropolitan locality. A transmission loss of not less thant 60 db is required for the ceiling, especially if air traffic is a present or potential source of noise. If the theater is located on a quiet site, it is unnecessary provide this much insulation for walls or ceilings. Where the site is subject to excessive earth vibrations, as such result from nearby bus or trolley lines, it is advisable not only to provide double walls, but also to isolate the inner walls of the auditorium, from the earth. The splayed walls and ceiling of the proscenium, the flat ceiling of the auditorium, and the lower portion of the side wall are designed to reflect useful sound upon the audience and accordingly are finished with reflective materials (suspended plaster ceiling, furred-out plaster walls, and plywood wainscot applied to randomly spaced wood strips). The aisles are covered with cork carpet in order to reduce the noise of footballs and the floor under the seats as covered with linoleum to reduce the noise of scoffing feet.

If the theater has a seating capacity of 270, a volume, V, of 40,000 cu. ft., and a total interior surface area, S, of 7,500 square feet.



Floor area	– 35 × 55	= 1925
Ceiling area		= 1925
Front wall	– 35 × 20	= 700
Rear wall		= 700
Side wall a	– 55 × 20	= 1100
Side wall b		= 1100
	S	= 7450 Sq. ft. (close to 7,500)

Volume

$35 \times 55 \times 20 = 38{,}500$ (close to 40,000)

Then, by the use of this equation (see reverberation time)

$$t_{60} = \frac{0.049\,V}{S\,[-2.30\,\log_{10}(1 - \bar{\alpha})]}$$

The total absorption required to give the optimum reverberation time is calculated as shown in step A of this table.

A. Required Absorption

	128 Cycles	512 Cycles	2048 Cycles
Optimum reverberation time in seconds	1.5	1.0	1.0
$-2.3\log_{10}(1-\bar{\alpha})$	0.174	0.261	0.261
$\bar{\alpha}$	0.160	0.230	0.230
Total square-foot-units of absorption required $= S\bar{\alpha}$	1200	1725	1725

Equation $$t_{60} = \frac{0.049\,V}{-2.30\,S\,\log_{10}(1 - \bar{\alpha}) + 4m\,V}$$

Should be used for larger auditoriums or for higher frequencies than those considered here.

We shall now determine the amount of additional absorptive material, if any, that should be installed if the room is to have the optimum reverberation time. This is done by computing the amount of absorption in the room without any special absorptive treatment; This value is then subtracted from the total required absorption of step A, the difference being the addition absorption that should be furnished. We shall carry out these calcula-

tions by first assuming that unupholstered chairs, are used and then comparing the results with similar computations based on the assumptions that upholstered chairs are used.

In the above table, the absorption furnished by the wall surface is tabulated in step B, If we add these values to those of step C, which gives the absorption supplied by chairs and audience, we find that the total absorption in the room, in the absence of any absorptive treatment, is: 862 square-foot-units (sabins) at 128 cycles; 1130 sabins at 512 cyles; and 1265 sabins at 2048. Hence, subtracting these values of absorption from corresponding values in step A, we find that the following amounts must be added to provide the optimum reverberation time at these frequencies: (1200 − 862) = 338 sabins at 128 cycles; (1725 − 1130) = 595 sabins at 512 cycles; and (1725 − 1265) = 460 sabins at 2048 cycles.

B. Absorption Furnished by Wall Surfaces

Absorptive Material	128 Cycles		512 Cycles		2048 Cycles	
	Abs. coef.	Abs., in sq-ft-units	Abs. coef.	Abs., in sq-ft-units	Abs. coef.	Abs., in sq-ft-units
Cork carpet, 380 sq ft	0.04	14	0.05	19	0.05	19
Linoleum floor, 2000 sq ft	0.04	80	0.04	80	0.04	80
Ceiling, 2000 sq ft	0.05	100	0.06	120	0.06	120
Wood wainscot, 1060 sq ft	0.06	64	0.06	64	0.06	64
Proscenium opening, 450 sq ft	0.30	135	0.40	180	0.50	225
Stage wall, 430 sq ft	0.05	21	0.06	26	0.06	26
Rear wall, upper side walls 1230 sq ft	0.05	61	0.06	74	0.06	74
Total absorption from above required materials	475		563		608	

C. Absorption Furnished by Unupholstered Chairs and the Audience

	128 Cycles	512 Cycles	2048 Cycles
	Abs., in sq-ft-units	Abs., in sq-ft-units	Abs., in sq-ft-units
90 unupholstered chairs	27 (0.3 per chair)	27 (0.3 per chair)	27 (0.3 per chair)
180 auditors in unupholstered chairs	360 (2.0 per person)	540 (3.0 per person)	630 (3.5 per chair)
Total absorption by chairs and audience	387	567	657

D. ABSORPTION FURNISHED BY UPHOLSTERED CHAIRS AND THE AUDIENCE

	128 Cycles	512 Cycles	2048 Cycles
	Abs., in sq-ft-units	Abs., in sq-ft-units	Abs., in sq-ft-units
90 upholstered chairs	180 (2.0 per chair)	270 (3.0 per chair)	270 (3.0 per chair)
180 auditors in upholstered chairs	540 (3.0 per person)	810 (4.5 per person)	900 (5.0 per person)
Total absorption by chairs and audience	720	1080	1170

Desirable acoustical conditions would not prevail, for there would be a large difference between the reverberation times for the relatively empty theater and full theater. This situation can be remedied by replacing the chairs with upholstered ones. Suppose they have the absorption listed in step D. Then, adding the absorption in D to the absorption supplied by the wall materials of step B as above, we find that the following amounts of absorption should be added: (1200 – 1195) = 5 sabins at 128 cycles; (1725 – 1643) = 82 sabins at 512 cycles; and (1725 – 1778) = –53 sabins (that is, subtract 53 sabins) at 2048 cycles; these values are neglible.

Hence, the analysis in the tables ABCD above leads to the conclusion that no special absorptive materials are needed in this theater in order to provide the optimum reverberation times of upholstered chairs are used; the total absorption furnished by the audience, chairs and the indicated materials for the walls, floor, and ceiling does not differ more than 5 per cent from total required absorption. This desirable outcome follows from the choice of a small volume per seat for the theater (148 cubic feet) and proper funishings, including the highly absorptive upholstered chairs. If a much larger volume per seat had been used, as is customary in the design of many theaters, it would have been necessary to add special absorbents to the walls or to the ceiling or to both. This should be avoided if possible because an increase of absorption would result in an unavoidable decrease in the average sound level of speech in the theater.

$$\text{Equation } L = 10 \log_{10} \frac{W}{a} + 136 \text{ db}$$

(principles of room acoustics)

Furthermore, when most of the required absorption is furnished by upholstered chairs, as it is in the theater here considered, the reverberation time is relatively independent of the size of the audience — a highly desirable condition.

It is necessary to control the reverberation on the stage. Reverberation times of the same values as those specified for the auditorium will be satisfactory. This condition is usually closely approximated if the stage is not excessively large and is equipped with a full set of flies and with side, rear, and overhead hangings of velours or monk's cloth. The hangings should be hung with deep folds, at least 100 percent being allowed for gathers. The reverberation times should be calculated by the procedure followed in the tables ABCD above. If additional absorption is required, it can be furnished by treating the upper walls or ceiling of the stage with a suitable type and amount of fiberboards or other absorptive material.

A small, enclosed set, made of reflective material (such as pressed fiberboard, plywood, painted canvas) and placed forward on the stage, affords the best means of projecting sound to the audience, and its use should be encouraged whenever feasible. Some tests conducted in one rather large theater show the importance of having the action take place on the front of the stage, and consequently of having an enclosed set to direct the speech to the audience. With a speaker on the front part of the stage, the syllable articulation of speech was 85 percent in the balcony. When the speaker moved to the rear part of the stage (with an open setting on the stage) the articulation was reduced to 60 per cent.

The intelligibility of speech in the little theater described in this section will be exellent. In general, it will not be necessary for the actors to raise their voices. They can therefore give their entire thought and feeling to the dramatic expression that will best portray the lines of the play, and they can act with the assurance that every word will be heard by the audience.

The Legitimate Theater

In this section, consideration will be given to legitimate theaters that are larger than the one described in the preceding section. Although the same general principles of design apply here with equal relevance, there is one important point of difference. In legitimate theaters, because of their larger size, speech is at a lower sound level that it is in little theaters. In fact, it frequently is not loud enough for good audition.

Therefore, it is of the outmost importance to design the shape of the auditorium so that it will provide the audience with the greatest possible amount of direct and of beneficially reflected sound. The divergence of the side walls, the slope of the overhead proscenium play, and the slope of the main ceiling of the auditorium should be carefully designed to reinforce the sound propagated to the audience, and some preferential reflection of sound should be provided for the rear seats under and in the balcony.

It is good acoustical design to keep the balcony overhang (depth) less than twice the height of the balcony opening, and to keep the balcony soffit reflective and inclined downward toward the rear wall. Heavily upholstered chairs, carpets on the aisles, and such absorptive treatment of the rear wall as is required to prevent objectionable reflections ordinarily provide satisfactory reverberation characteristics in the balcony recess. When the ratio of depth to opening height does not exceed 2, this space can be regarded as an integral part of the auditorium, and it then is not necessary to maie separate calculations or reverberation in the two spaces — the main part of the auditorium and the balcony recess. In routine calculations of reverberation time, it is customary to regard these two spaces as one single volume and the stage recess as another. It is important that the stage have appoximately the same reverberation characteristic as the auditorium. For such computation, the coefficients of absorption in the table below are applicable to the stage opening.

ABSORPTION COEFFICIENTS FOR STAGE OPENINGS

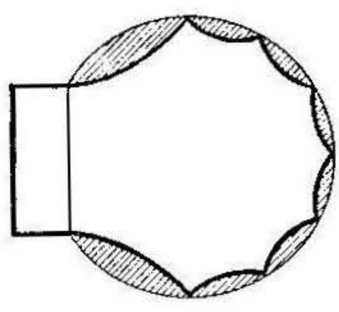
Frequency in cyles	128	512	2048
Absorption coefficient	0.30	0.40	0.50

If a theater is to be used for musical as well as dramatic productions, the reverberation characteristic should be based upon the requirements for both music and speech, and the absorptive materials should be carefully located to favor a uniform average rate of decay in all parts of the theater.

Outside noises are calculated to determine the insulation required. Noise of inside origin, such as that from ventilating equipment, should be suppressed.

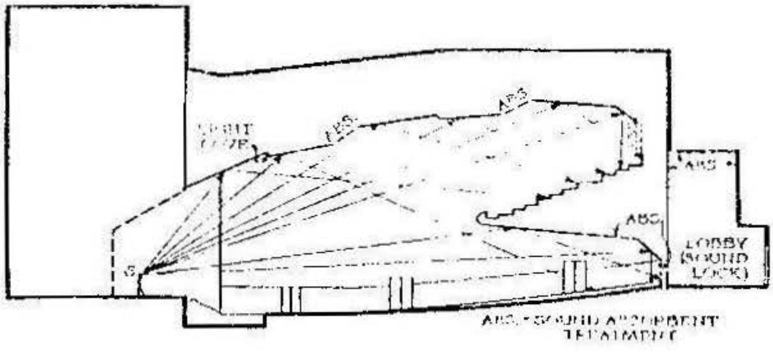
Theaters which are circular or elliptical in plan, or theaters with domed or cylindrical ceilings, are *especially likely to give difficulty*, although when the curved surfaces are well broken or coffered, or treated with a material having a coefficient of absorption in excess of 0.70, the difficulty due to the curved surfaces may be largely overcome. For example, consider the acoustical treatment that was applied to one theater having a circular plan with the stage opening forming a part of the cylindrical walls. If the walls of this theater had been finished with reflective materials there would have been a very pronounced focusing of sound at a point about half way between the rear and the center of the auditorium. To overcome this anticipated defect, two layers of 1½ inch fibrous blanket, separated by a 2 inch air space and covered with a perforated membrane, were applied to the side and rear cylindrical walls in the form of a band extending in length approximately three fourths of the way around the interior, and in height from about three feet up to 16 feet from the floor. This expedient gave satisfactory results.

The front portions of the side walls were finished with hard material to give helpful reflection toward the central and rear parts of the theater. Another method of handling the problem of large concave surfaces is to divide them into secondary convex surfaces as in this figure. Although it is possible to



Circular floor plan modified by convex diffusing surfaces which greatly reduce the focusing and creeping effects.

treat concave surfaces in such a way as to overcome most of the acoustical defects they produce, it is preferable to use forms are free from undesirable curvatures. This does not mean that concave surfaces are always to be avoided, but if they are employed without careful consideration they may be lead to disastrous results.



The figure above shows an acoustical study of a longitudinal section of a theater in which the ceiling surfaces have been designed to reinforce sound by reflection. The overhang of the balcony is short, and the opening under the balcony is high; therefore adequate sound will reach the rear seats under the soffit. These seats, which are usually the poorest ones in most theaters, are further benefited in this design by the reflections of sound from both the splayed walls and the ceiling of the proscenium. The main part of the ceiling has a gently rising slope which provides the most favorable reflection of sound. Heavily upholstered chairs are used throughout, and aisles are carpeted over a 1/2-inch carpet pad. Most of the absorption required to provide the optimum reverberation is applied to the rear wall, under and above the balcony, to prevent echoes and interfering reflections from these surfaces.

A 2-inch or 3-inch mineral-wool blanket covered with perforated plywood, or similar facing, is suitable here. The highly absorptive material should not extend below the height of the heads of the audience. Below this level the rear wall is paneled wainscot, which with the similar side wall wainscot provides much of the required low-frequency absorption. Calculations similar to these described in the table (absorption) coefficients) above (using equation t_{60}

$$= \frac{0.049\ V}{-\ 2.305\ \log_{10}(1-\alpha\ +\ 4_{mV})}$$

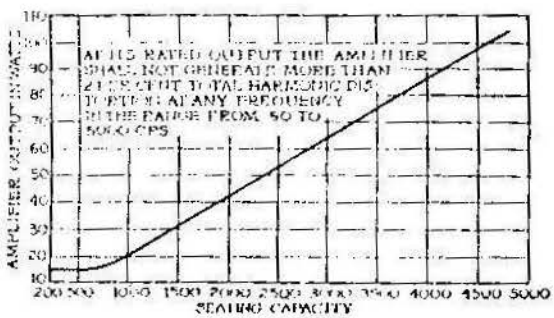
for the computation of reverberation times (should be made to determine the kind and amount of additional absorptive material, if any, required to give the optimum reverberation characteristics. The directions and procedures outlined in the preceding section for sound insulation and for other acoustical aspects of the little theater also applied to the larger legitimate theaters.

An enclosed set, like that indicated by the dotted lines of the figure above, should be used whenever possible. The set reflects toward the audience a larger and much-needed amount of sound which originates on the stage; and which would otherwise reverberate and be lost by absorption in the upper part of the stage. Sets with parallel side walls may cause flutter echoes. On the other hand, the side walls should not diverge too rapidly. If they splay outward too much the performers on a large stage may have large difficulty on hearing each other.

Motion Picture Theaters

The general cosiderations of shape discussed in the detail in chapter 6 (Acoustical Design of rooms) apply to motion picture theaters. Furthermore, certain admonitions given in that chapter are especially pertinent here. For example, concave rear walls, parallel side walls, parallel ceiling and floor, and surfaces that give long-delayed reflections in the seating area should be avoided. Long narrow theaters often have very poor acoustics they are likely to require so much acoustical power from the sound system, in order to give adequate sound level in the rear seats, that the loudness will be excessive in the front and central seats.

Because sound is reproduced in motion picture theaters by means of electro-acoustical equipment that can furnish adequate sound levels in all parts of even very large theaters the acoustical design of the cinema is not, so dependent on beneficial reflections from the walls, proscenium, splays, and ceiling as is the design of the legitimate theater. The average sound level of speech in the cinema is usually about 65 db for dialogue, which is 10 to 15 db higher than the average unamplified speech level in the legitimate theater The acoustical power required to maintain this level depends on the size of the theater The minimum power requirements of the amplifier that actuates the loudspeaker is given in this figure.

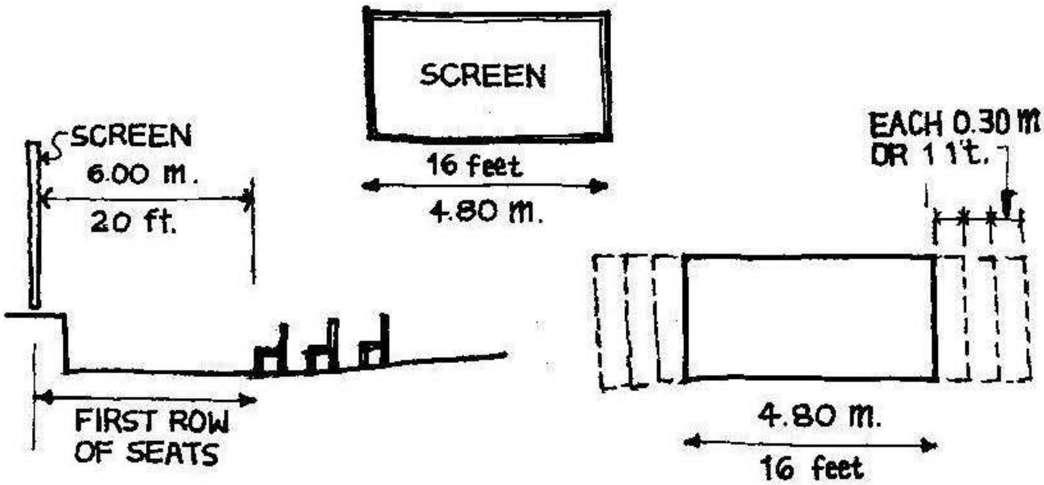


Minimum requirements for the amplifier power-handling capacity in the sound system of a motion pictue theater.

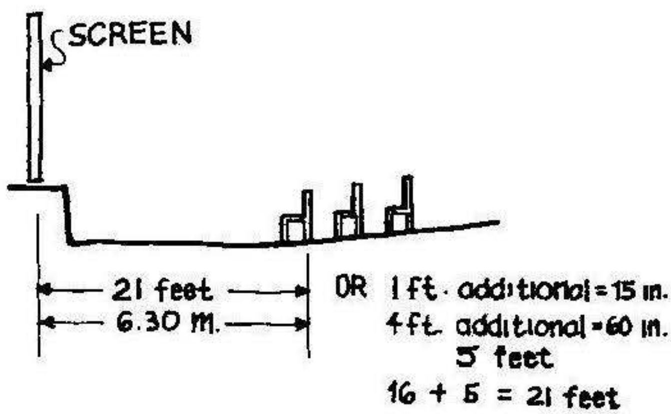
The amplifier rating is shown as a function of the seating capacity of the house. For example, a theater seating 1000 should be equipped with an amplifier having a power output of at least 20 watts

Lengths greater than about 150 feet should be avoided in order to prevent a noticeable delay in the arrival of the sound to persons in the rear of the theater. It requires about 1/7 second for sound to travel 150 feet. The lack of synchronism between sight and sound becomes quite annoying when the difference exceeds about 1/7 second. Since the length of the theater may be as great as double the width, it is necessary to design the side walls, floor, and ceiling so as to minimize the attention of the sound transmitted toward the rear seats. Sound which is propagated over an abrsorptive surface, such as an audience or an acoustically treated ceiling, is greatly attenuated. Hence the floor should rise steeply toward the rear, the loudspeakers and screen should be well elevated, and the ceiling and side walls should neither be highly absorptive nor obstruct unduly the flow of sound from front to rear. Splays and other functional deviations in the wall and ceiling contours can be used to give the proper diffusion without hindering the efficient transmission of sound to the rear of the auditorium.

The motion picture research council recommends, for proper viewing and listening conditions, that the first row of seats be at least 20 feet (6.00 m.) from the screen — for screen widhts not greater than 16 feet (4.80 m.). For wider screens, the first row of seats should be back an additional 15 inches for each foot of screen width over 16 feet.

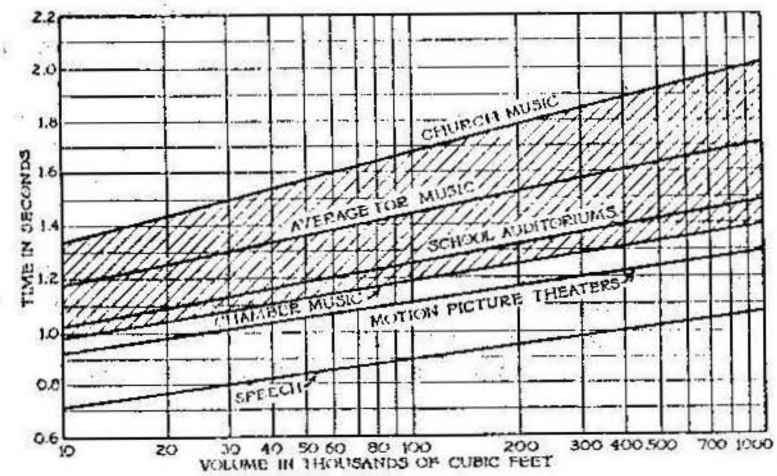


ex. if the width of the screen is 20 feet or 4 feet more than 16 feet (6.00 or 1.20 more than 4.80 m.) add 15 inches or (0.33 m.) for the first row of seat.

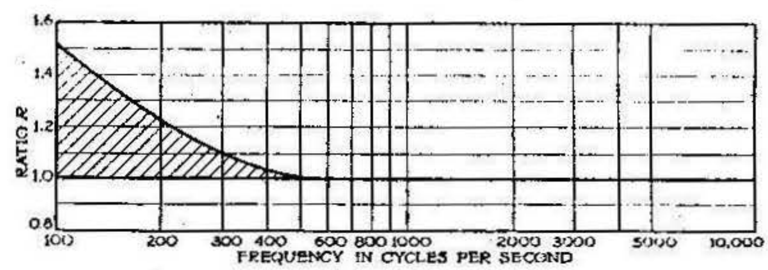


If there is a balcony, its depth should not be more than three times the height of the balcony opening. A relatively deeper overhang can be tolerated here than for a legitimate theater, since the average speech levels in a cinema are somewhat higher. The balcony soffit should slope downward toward the rear, and should not be absorptive. (See chapter 6 on Acoustical Design of Rooms) for other features of design.

A volume per seat of 125 to 150 cubic feet is a good figure to use in determining the optimum volume, the lower value being preferable. The design of a house with a low volume per seat has several advantages over designs with the visual larger values, acoustically and otherwise. The building cost is reduced; the cost of the corresponding smaller air — conditioning equipment and, to a much lesser extent, of the sound-amplification system) are likewise reduced; and the optimum reverberation can be obtained with the use of little or no special sound absorbents added to the walls and ceiling, if thick carpets are used on the aisles and heavily upholstered chairs are installed. The optimum reverberation times for motion picture theaters can be determined from these figures.



Optimum reverberation time at 512 cycles for different types of rooms as a function of room volume.



After calculation of the total square-foot-units (sabins) of absorption supplied by the upholstered chairs, audience, carpeting, and the walls and ceiling, the total required number of sabins of absorption that must be added is obtained by subracting from the total number of required units the units of absorption furnished by chairs, audience, (assume a 2/3 capacity audience), and all the boundaries of the auditorium. Absorptive material should be applied to the rear wall to eliminate "slap-back". Additional absorptive material may be applied to the side walls in accordance with the general principles and recommendations of Chapter 6.

Treatment of the walls behind the screen with highly absorptive material prevents sound radiated from the back of the loudspeakers from the being reflected to the audience. It also suppresses acoustical resonances that occur on some stages. Mineral — wool blankets have been used in many theaters to treat this area. The surface of the backstage acoustical treatment should be very dark, preferable black, in order to avoid light reflection from it. As indicated in Chapter 5, the absorption characteristics of an acoustical material can be enhanced, especially at low frequencies, by furring it out from the wall. If a blanket consisting of glass wool is used, it should be at least 2 or 3 inches thick and have a density of about 4 pounds per cubic foot. The floor between the screen and the first row of seats also should be highly absorptive, in order to prevent sound from reaching the audience in the front seats be reflection from this area. Such reflections contribute to the loss of "intimacy"; that is, the loss of feeling that the sound is actually coming from the screen. They may be suppressed by covering the stage floor with heavy carpets over 1-inch ozite or similar absorptive pad.

In many respect the acoustical problems of motion picture and legitimate theater are similar. Both should be properly insulated against noise according to the principles of Chapters 8 to 10. In general, a slightly greater noise level can be tolerated in motion theaters than in legitimate theaters because of the higher speech level. The average "film" (background) noise" level is about 35 db, whereas the average audience noise level in a cinema is about 40 to 45 db. Since the projection booth is a potential source of noise, all available interior surfaces should be heavily treated with fireproof acoustical material, such as a 2- to 3-inch mineral-wool blanket covered with perforated transite. Double panes of glass of different should fit tightly in their frames so that there are no threshold cracks. It also is helpful to cover with absorptive material the peripheral surfaces separating the double windows. The wall between the projection room and the auditorium should have a transmission loss of not less than 35 db at 128 cycles and not less than 45 db at 512 to 2048 cycles.

School Auditoriums

The school auditorium usually serves a wide range of functions. It is used as an assembly room, large classroom, theater, cinema, concert hall, community auditorium, and it houses a host of other activities. The elements of design given in Chapter 6, regarding shape, size, reverberation, and diffusion, are applicable here. Furthermore, the principles and practice of noise control as described in Chapter 8 to 10 should be followed scrupulously.

In regard to theatrical uses, most school administrator and instructors of drama expect the *impossible* when they produce stage plays in a large auditorium without the benefit of a high-quality sound-amplification system. Auditoriums which are to be used without sound-amplication, even if only occasionally, should not have volumes in excess of the following:

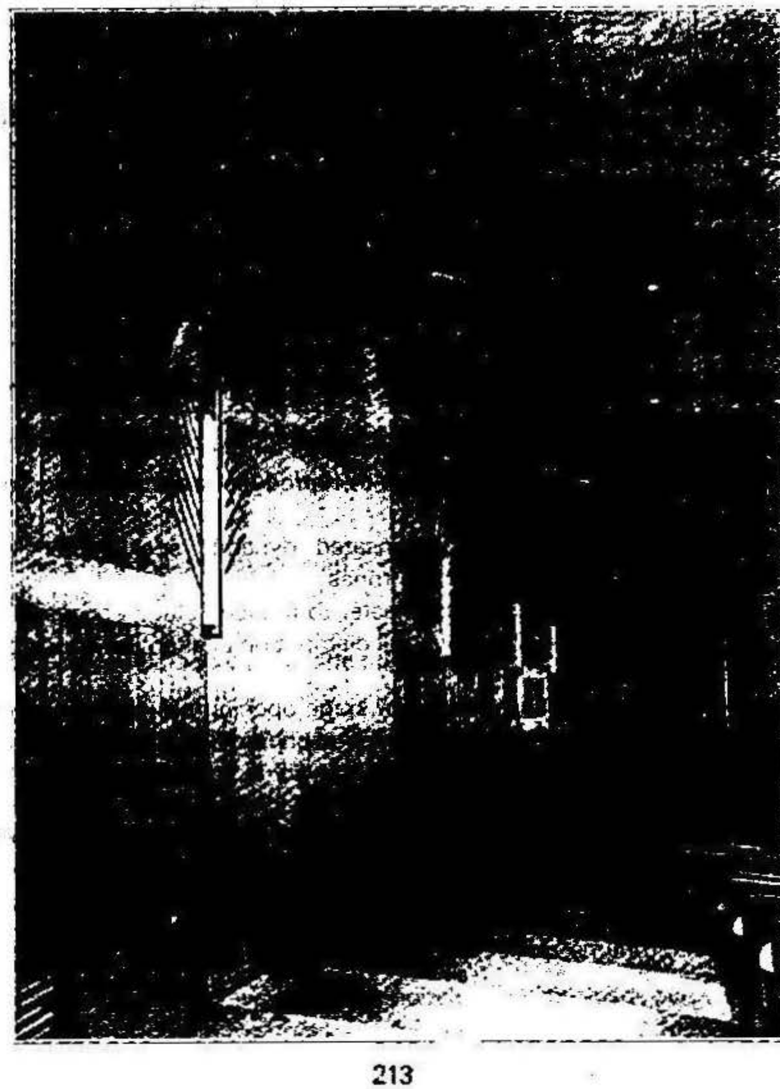
For elementary schools, about 40,000 cubic feet;
For high schools, about 50,000 cubic feet;
For colleges and universities about 60,000 cubic feet;

(These volume include the volume of the recess under the balcony but not the volume of the stage recess.) A great deal of dissatisfaction will be eliminated by avoiding the design of larger auditoriums for schools. If for any reason it should become necessary to construct a larger auditorium, provision should be made for sound reinforcement for speakers with weak voices, for occasional musical programs. Nothing less than a stereophonic sound system will be entirely satisfactory for theatrical purposes (see Chapter 7).

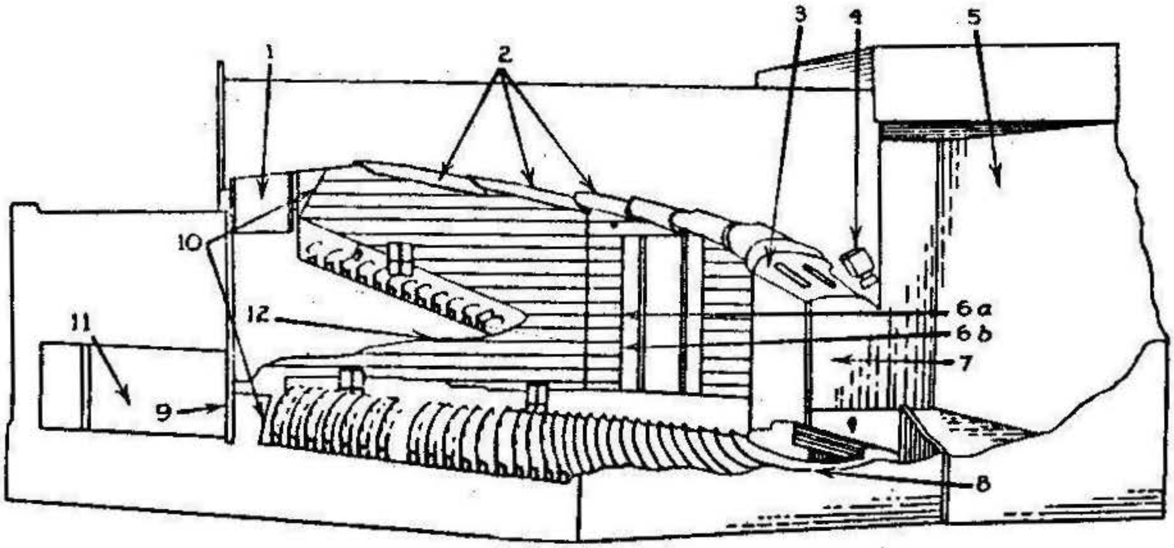
The auditorium should be located in a quiet section of the campus. If it forms a part of another building, it should be thoroughly insulated from the remainder of the building. There should be two sets of tightly fitting doors between the auditorium and the adjacent corridors or the outdoors. If a high degree of insulation is required, it will be helpful to dispense with windows. With the increase in airplane traffic, it has become increasingly necessary to eliminate windows; with the good air-conditioning systems available, they are no longer a necessity. Any noise from the ventilating or other mechanical equipment should be adequately suppressed. The floor should be covered with linoleum or some

other soft covering. The chairs should be heavily upholstered, of a rigid, substantial construction, and securely fastened to the floor so that there will be no creaking or squeaking.

It is necessary to make a compromise between the optimum acoustical properties for speech and for music in order that the the school auditorium may best serve its diverse uses. The exact calculation of reverberation involves a three-space problem: the stage recess, the main part of the auditorium, and the recess under the balcony. However, if the stage has an enclosed set and if the balcony recess is not too deep, the calculation of reverberation time reduces to a one-space problem. In order to make this simplification, it is assumed that each of these three spaces contains an appropriate amount of absorption to permit a uniform average rate of growth or decay of sound in all parts of the auditorium. The complete set of hangings required for the stage setting ordinarily will supply a sufficient amount of absorption for the stage recess. In fact, a full set of stage hangings may make the stage too dead for musical settings. For this reason it is advisable to provide an enclosed wood veneer or heavily painted canvas set for musical programs, such as shown by the dotted lines in the previous figure, longitudinal section of a legitimate theater. If upholstered chairs are provided and the aisles of the floor are carpeted, the recess under the balcony ordinarily will not require additional absorptive treatment of its side walls in the strips, panels, or patches to give added diffusion; if none is required, it may be necessary to introduce splays, or other means of insuring proper difussion. An example of good side wall design is shown in this figure.



The figure below shows a section of a high school auditorium that incorporates the essential characteristics of good acoustical design. The following features were given careful consideration during the design and construction of the auditorium the floor plan, the elevation of seats, the diverging proscenium splays, the functional ceiling, the shape and dimensions of the balcony recess, the control of reverberation and diffusion by alternate horizontal strips of absorptive tile and reflective plaster for the side walls, the upholstery of the chairs, the stage furnishings (including an enclosed reflective stage set for musical programs), the planned insulation against outside noise, the control of inside noise, and the sound-amplification system.



Scale: 3/16 = 1'0"

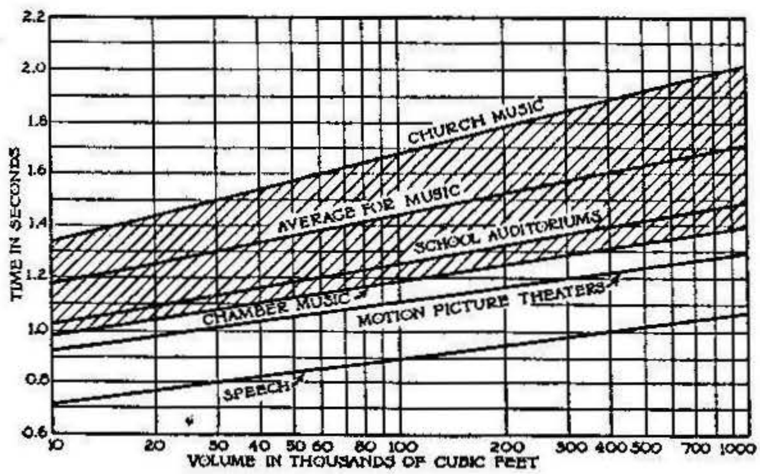
1. Acoustically treated projection booth with sound-amplification equipment and controls for sound monitoring.
2. Ceiling planes reflect sound to all parts of the auditorium.
3. Three-channel public address system to reproduce stage sound in "auditory perspective."
4. High-fidelity speakers: bass-compensated dynamic speaker for low tones; high-frequency directional horns for high tones.
5. Backstage treated with acoustical plaster to reduce "stage echoes."
6. Acoustical treatment on walls; over-all distribution in alternate bands of (*a*) acoustic tile and (*b*) hardwall plaster.
7. Proscenium splays; horn-like shape of stage opening projects sound to audience.
8. Upholstered seats; absorption value of each seat equivalent to that of a person's clothing.
9. Double doors to foyer insulate against external noises.
10. Slanting rear walls on main floor and balcony reflect sound down toward rear seats.
11. Acoustically treated foyer to reduce external noises.
12. Streamlined balcony improves flow of sound to rear seats.

Many school auditoriums, especially in small towns, are used for community purposes-

of light in the wave spectrum with relation to other wave phenomena of various frequencies.

Civic Auditoriums

Many schools auditoriums, especially in small towns, are used for community purposes-town meetings, debates, concerts, and a variety of other gatherings. But as a town grows to a city, there develops a need for a separate civic auditorium to serve the above purposes and a number of others such as dances, bazaars, conventions, and activities that require (1) a level hardwood floor and (2) readily removable chairs. The present section is concerned with the latter type of auditorium. The two features just mentioned introduce acoustical problems that do not occur in the usual auditorium. The level floor, especially if it extends more than about 15.50 meters (50 ft) from the stage, requires the stage to be as high lines will allow. The portable chairs generally will not be upholstered, or they will have only thin pads of soft and absorptive material on the seats and backs. These chairs furnish much less absorption than do fully upholstered ones (the fixed chairs should be heavily upholstered, of the type previously advocated in this chapter for theaters and school auditoriums.). It usually will be necessary to compensate for the lack of absorption in the chairs by the introduction of absorptive strips, panels, or patches on the walls and ceiling in such amounts as will provide the optimum reverberation and good diffusion. The optimum reverberation characteristics will be provided in most cases as if the curve which applies to school auditoriums in this figure is used.



Since civic auditoriums are often used for small audiences and since the chairs are often upholstered, it is advisable to provide the optimum reverberation for one half of capacity audience. If a room has a volume of more than about 50,000 cubic feet, a sound-amplification system is necessary. The loudspeakers should be located somewhat higher than they would be in an auditorium with a sloping floor.

All the acoustical problems considered in the previous sections of this chapter, namely those relating to theaters, cinemas, and school auditoriums, are likely to arise in planning the acoustics of civic auditoriums, and it is recommended that these sections be carefully reviewed. The acoustical problems relating to the design of a municipal auditorium become increasingly complex and difficult as the size of the auditorium increases. Echoes and interfering reflections become much more probable, and therefore appropriate plans should be worked out at the very start of the design to avoid these defects and to insure a good distribution of sound to all seats. Acoustical studies should be made of all feasible shapes and arrangements supplemented by model testing, if there are any uncertainties determining the best plans.

Existing municipal auditoriums are notoriously defective in regard to acoustics. Until recently, most of them were excessively reverberant. Many of these have been "corrected" by "acoustical treatments", that is, by adding acoustical tile or plaster to the entire ceiling or to almost every available surface that can be so treated. This has given quite satisfactory results in many cases. However, in some instances, the auditoriums have been overtreated, or mistreated by placing the absorptive material in the wrong places, and the correction of other serious defects has been overlooked. For example, a study was made recently of a municipal auditorium seating 1,800 persons. At the time of construction, acoustical plaster was applied to all side walls the rear walls was treated with a thin acoustical tile, and the entire ceiling was treated with thin fiberboard applied directly to concrete ceiling slabs. The stage was furnished with overhead, side and rear hangings of unlined velours. As a result the auditorium was somewhat overtreated at medium and high frequencies. Complaints were made about the acoustics, most of them by the artists who sang or played solo instruments in this auditorium. They averred that their voices were "smoothered", that they feel unable to "project" sound out into the audience.

The management, heeding these complaints, added still more absorptive treatment — a burplap type of material festooned between the exposed trusses — and made the situation worse. Instead, the following correctives should have been supplied:

1. A stage setting of ¼ inch plywood with overhead and side splays.
2. A suspended ceiling designed in accordance with the principle of chapter 6. To give beneficial reflections and made of a material that would add considerable absorption at the high frequencies.
3. Replacement of the thin absorptive tile on the rear wall with a material that is highly absorptive at low as well as high frequencies.
4. A high quality sound amplification system. These correctives would not provide ideal acoustics in this auditorium but they would eliminate the objectionable defects and make the building quite satisfactory for its many functions.

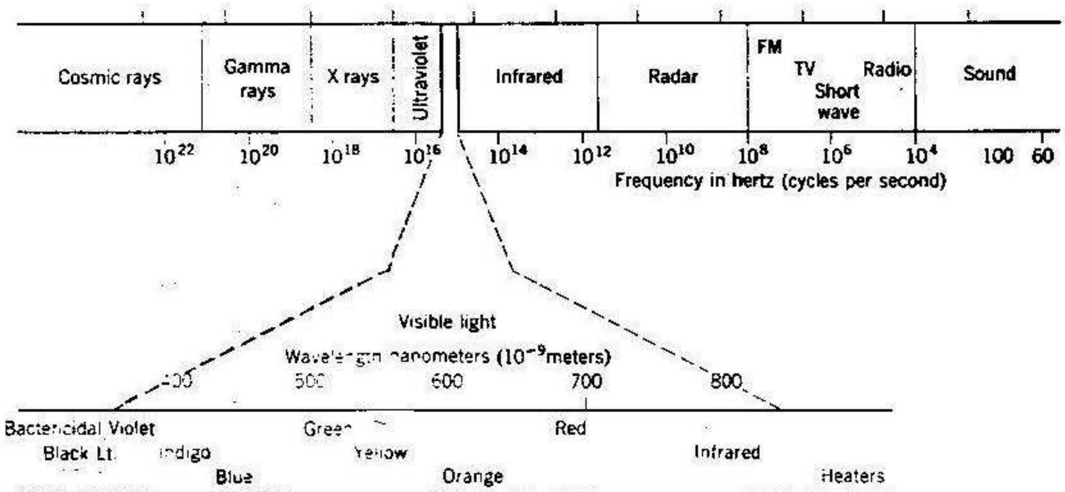
12

FUNDAMENTALS OF LIGHTING

PHYSICS OF LIGHT

LIGHT AS RADIANT ENERGY

Light is "visually evaluated radiant energy" or more simply, a form of energy which permits us to see. If light is considered as a wave, similar to a radio wave or an alternating current wave, it has a frequency and a wave length. The figure below shows the position of light in the wave spectrum with relation to other wave phenomena of various frequencies.



From the chart we see that even the longest wavelength light (red) is a much higher frequency than radio and radar, and that visible light comprises only a very small part of the wave energy spectrum. Yet it is this energy that makes possible our sight and with which we are here concerned. Color is determined by wavelength. Starting at the longest wavelengths with red, we proceed through the spectrum of orange, yellow, green, blue, indigo, and violet to arrive at the shortest visible wavelengths (highest frequency)

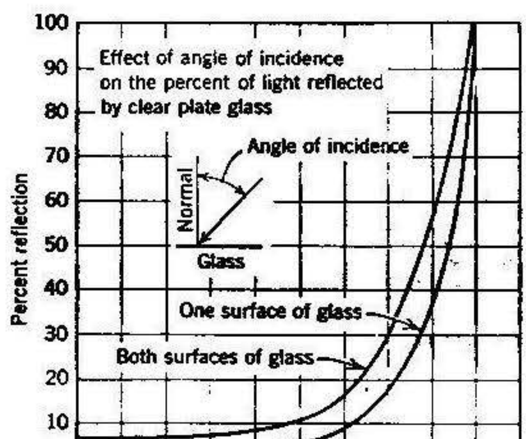
When a light source produces energy over the entire visible spectrum in approximately equal quantities, the combination of colored light produces white as is the case with the sun, whereas a source producing energy over only a small section of the spectrum produces its characteristics colored light. Examples are the blue-green clear mercury lamp and the yellow sodium lamp.

Fundamental Laws of Light

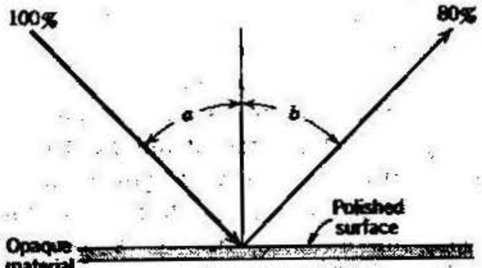
Design of lighting installations is possible because light is predictable, that is, it follows certain laws and exhibits certain fixed characteristics. Although some of these are so well known as to appear self-evident, a review is in order.

The *luminous transmittance* of a material such as a fixture or diffuser is a measure of its capability to transmit incident light. By definition, this quantity known variously as *transmittance, transmission factor, or coefficient of transmission* is the ratio of the total emitted light to the total incident light. In the case of incident light containing several components passing through a material that displays selective absorption, this factor becomes an average of the individual transmittances for the various components and must be used cautiously. A piece of frosted glass and a piece of red glass may both have a 70% transmission factor but obviously affect the incident light differently. In general then, transmission factors should be used only when referring to materials displaying nonselective absorption. Clear glass, for instance, displays a transmittance between 80 and 90%, frosted glass between 70 and 85%, and solid opal glass between 15 and 40%.

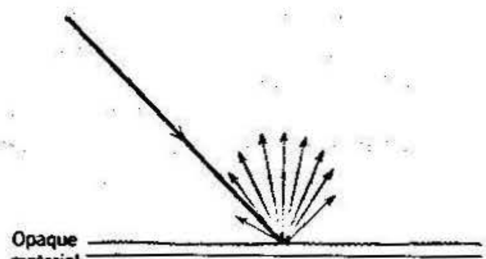
Similarly, the ratio of reflected to incident light is variously called *reflectance, reflectance factor,* and *reflectance coefficient*. Thus if half of the amount of the light incident on a surface is bounced back, the reflectance is 50% or 0.50. The remainder is absorbed, transmitted or both. The amount of absorption and reflection depends on the type of the material and the angle of light incidence, since light impinging upon a surface at small (grazing) angle tends to be reflected rather than absorbed or transmitted.



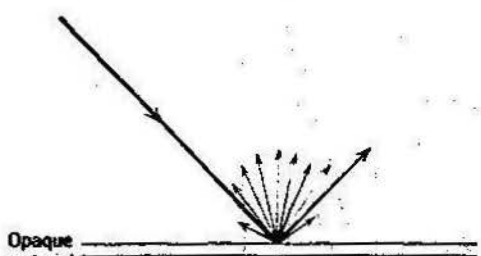
An example of almost perfect reflection from an opaque surface would be that from a well-silvered mirror while almost complete absorption takes place on an object covered with lamp black or matte finish black paint. The effect of the material finish on reflection is shown in figure below.



Specular reflection

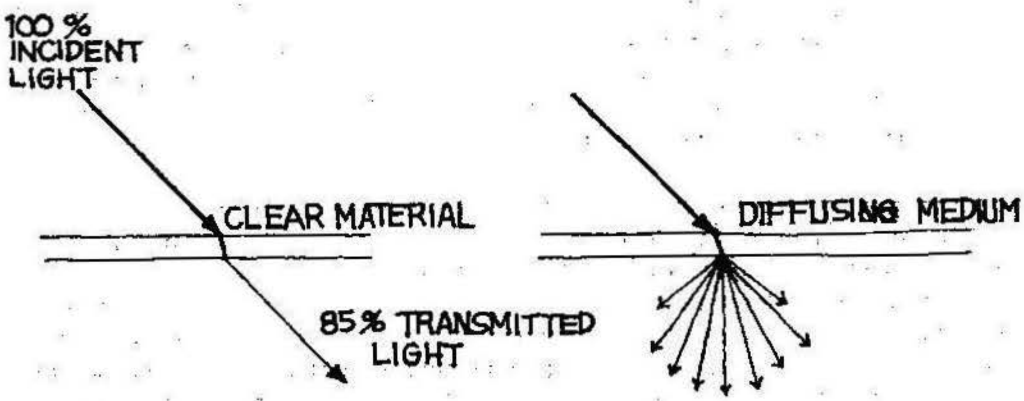


Diffuse reflection



Combined specular and diffuse reflection

If the reflection takes place on a smooth surface such as polished glass or stone it is called specular reflection, as in figure (a). If the surface is rough, multiple reflection takes place on the many small projections on the surface, and the light is diffused as in figure (b). Since the reflection factor is a measure of total light reflected, it does not depend on whether the reflection is specular or diffuse, or a combination of both, as shown in figure (c). Diffuse transmission takes place through any translucent source such as frosted glass, white glass, milky plexiglas, tissue paper and so on. This diffusing principle is widely employed in lighting fixture to spread the light generated by the bulb or tube within the fixture. Diffuse and non diffuse transmission are illustrated in figure (a) and (b).



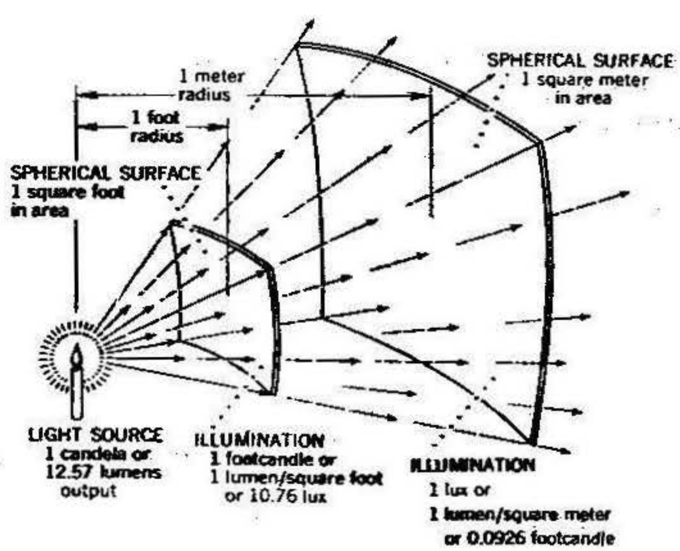
NONDIFFUSE TRANSMISSION
(a)

DIFFUSE TRANSMISSION
(b)

Terminology and Definitions

The *candlepower* (candela), abbreviated cp (cd), is the unit of luminous intensity. It is analogous to pressure in a hydraulic system and voltage in an electric system and represents the force that generates the light that we use.

An ordinary wax candle has luminous intensity horizontally of approximately one candlepower (candela), hence the name. The candlepower and candela have the same magnitude. A candle rediates light equally in all directions. If we imagine such a source surrounded by a transparent sphere of one foot (meter) radius (see fig. (a) below), then by definition the amount of luminous energy (flux) emanating from one square foot (meter) of surface on the sphere is one *lumen [lumen]* abbreviated lm.



Since there are 4π sq. ft. (meters) surface area in such a sphere, it follows that a source of one candlepower (candela) intensity produces 4π or 12.57 lm. The lumen is the unit of light quantity, and in terms of power is equal to 0.0015 w. (it therefore also follows that a l-cp (cd) source produces 12.57 x 0.0015 w, that is 0.0189 w or approximately 1/50 w of luminous energy). The lumen, as luminous flux, or quantity of light is analogous to flow in hydraulic systems and current in electric systems.

One lumen of luminous energy incident on one square foot of area produces an *illumination of one footcandle*. (fc). Restated, illumination is the density of luminous energy, expressed in terms of lumens per unit area. If we were to consider a lightbulb to be analogous to a sprinkler head, the amount of water released would be the lumens and the amount of water per square foot of floor area would be the foot candles. When the area is expressed in square feet the resulting illumination is footcandles; when the area is in square meters, the illumination is expressed in lux (lx). Thus, the SI unit (metric), lux, is smaller than the corresponding unit, footcandles, by the ratio of square feet to square meters, that is

10.764 lux = one footcandle

or

multiply footcandle by 10.764 to obtain lux

restating the above mathematically:

$$\text{footcandles} = \frac{\text{lumens}}{\text{square feet of area}}$$

$$\text{fc} = \frac{\text{lm}}{\text{sq. ft.}}$$

and

$$\text{lx} = \frac{\text{lumens}}{\text{square meters of area}}$$

$$\text{lx} = \frac{\text{lm}}{\text{sq. m.}}$$

As an approximation (8% error)

$$10 \text{ lx} = 1 \text{ fc}$$

Example:
A 40 – W, 430- ma (milliampere), 48 – in. Fluorescent tube produces 3200 lm. What is the illumination on the floor of a 10-sq. ft. rm assuming 40% overall efficiency and uniform illumination?

Solution

$$\text{useful lumens} = 0.4 \times 3200 = 1280$$

$$\text{fc} = \frac{1280}{10 \times 10} = 12.8$$

$$\text{lx} = 12.8 \times 10.76 = 137.7$$

Calculating lux directly:

$$\text{lx} = \frac{1280}{10 \times 10} \times (3.28 \text{ ft/m})^2 = 137.7$$

By approximating:

$$\text{lx} \simeq 10 \text{ fc} \simeq 128$$

Footcandle illumination at a point can also be computed from intensity as shown in the next section on inverse square law. A footlambert, the conventional unit of luminance or brightness, is defined as the luminance of a surface reflecting, transmitting, or emitting l lumen of illumination per square foot of area, in the direction ***being viewed.*** This latter qualification is important since many surfaces (fabrics, for instance) exhibit different luminances at different angles. This unit has no readily conceivable mechanical or electrical analogy. The brightness of a *non luminous* diffusely reflecting surface is equal to the product of the illumination falling on the surface and the reflectance of the surface, that is,

luminance = illumination x reflectance

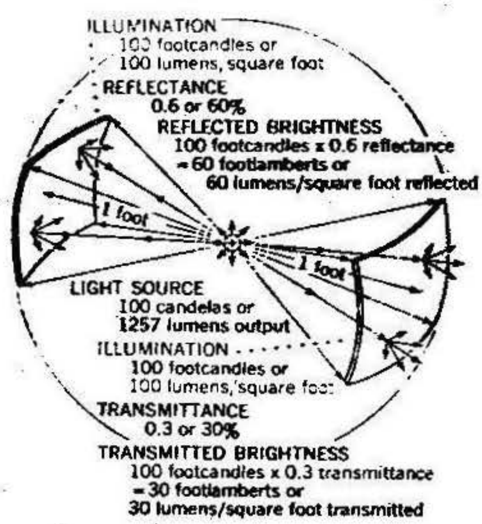
or

footlamberts = footcandles x reflectance factor

or fl = fc x RF

Thus a source that causes 100 Lm fall on a l sq. ft. surface with a diffuse reflectance of 60% has brightness of

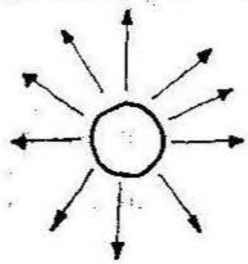
luminance = 100 lnm x 60% RF
= 60 fl



(b)

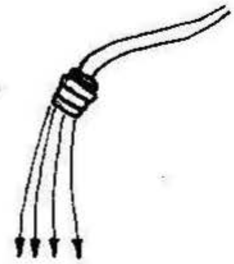
CONCEPT OF QUANTITY OF LIGHT

LIGHT RADIATING FROM BULB



LIGHT RADIATING FROM SUN

IS LIKENED TO

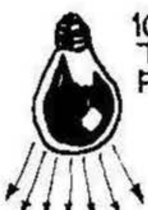


FLOW OF WATER FROM A HOSEPIPE

THE OUTFLOW OF LIGHT FROM A SOURCE WOULD BE MEASURED IN LUMENS.

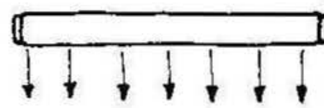
QUANTITY OF WATER DELIVERED WITH HOSE IS MEASURED IN LITERS/minute.

ANALOGY



100-WATTS TUNGSTEN FILAMENT LAMP

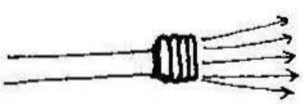
LIGHT OUTPUT OF 1200 LUMENS



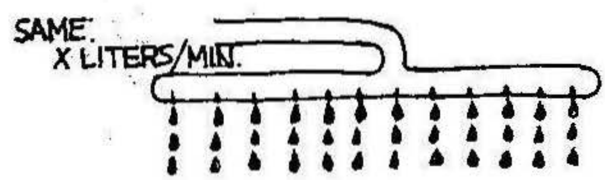
20 W FLUORESCENT TUBULAR LAMP

LIGHT OUTPUT SAME OF 1200 LUMENS BUT LESS BRIGHT BECAUSE THE LUMENS ARE EMITTED FROM OVER A MUCH LARGER AREA

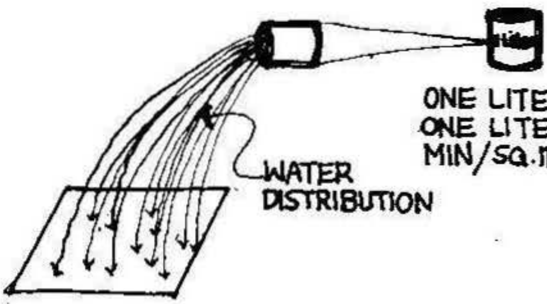
THIS IS COMPARED TO WATER FLOW-OR A HOSE WITH A SMALL NOZZLE GIVING AN INTENSE NARROW JET



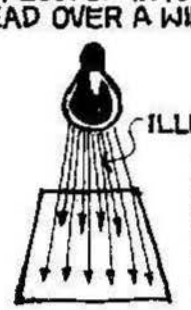
X LITERS/MIN.



ANOTHER HOSE WHICH WHILE DELIVERY THE SAME NUMBER OF LITERS/min. - WAS EMITTING ITS OUTPUT THROUGH A SPRAY NOZZLE WHICH BREAKS THE FLOW UP INTO FINE DROPLETS SPREAD OVER A WIDE ANGLE.



ONE LITER/MIN.
ONE LITER PER MIN/SQ.m



ILLUMINANCE

EACH SQUARE METER OF SURFACE RECIEVED SO MANY LUMENS THUS ONE LUMEN/SQ.m. THIS IS A UNIT CALLED **LUX**

Reflecting surfaces that derive their brightness from incident illumination are known as secondary sources Primary sources are those that generate light and transmit directly to the eye. The largest and best known primary and secondary brightness sources are the sun and the moon, respectively. The same unit of luminance, the footlambert (fl) is used for a luminous surface that either emits (self-luminous) or transmits light. As stated above, a surface emitting or transmitting an average of l lm / sq. ft. has a luminance of a transilluminated source is equal to the product of the illumination and the transmision factor, that is

$$\text{luminance} = \text{illumination} \times \text{transmission factor}$$

$$\text{or} \quad \text{fl} = \text{fc} \times \text{TF}$$

Thus, a source of 100 lm behind a translucent diffusing material one square foot in area, with a transmission factor of 30% exhibits a brightness of

$$\text{luminance} = 100\ \text{lm/ sq. ft.} \times 0.3$$
$$= 30\ \text{fl (see fig. (b) above)}$$

For an emitting surface:

Luminance = lumens emitted per square foot. Thus a surface emitting uniformly 100 lm / sq. ft. has a brightness of 100 fl.

In SI units (metric), the unit of brightness is the lambert (1) which is defined as the luminance of a surface reflecting, transmitting, or emitting one lumen per square centimeter, Since this unit is much greater than that normally used is the millilambert (ml). The relations between the units are

$$\text{lamberts} = 1.076 \times 10^{-3}\text{fl}$$
$$\text{millilamberts} = (1.076 \times 10^{-3})\ (1000) = 1.076\ \text{fl}$$

The footlambert is slightly larger than the millilambert. To convert, multiply the footlambert by 1.076 to obtain the millilambert.

as an approximation

$$\text{ml} = \text{l fl}$$

Example:

a fixture with a 2x4 ft. plastic diffuser having a transmittance of 0.8 and illuminated by four 3200 lm lamps, would have (assuming 100 % use of the light flux), a luminance of:

$$\text{luminance} = \frac{\text{transmitted lumens}}{\text{area}}$$

$$= \frac{\text{generated lumens} \times \text{transmission factor}}{\text{area}}$$

$$\text{luminance} = \frac{4 \times 3200\ \text{lm} \times 0.8}{2 \times 4\ \text{sq. ft.}}$$

$$= 1320\ \text{fl}$$

Each fluorescent tube has a luminance of **3200 lm** divided by the tube surface area. The T-12, 4 ft. tube has an area of πx diameter.

$$\pi \times 1.5 \times 48 = 226.5\ \text{sq. in.} = 1.58\ \text{sq. ft.}$$

This gives for a luminance for a 48- in., T-12 tube of 3200 / 1.58 or approximately 2000 fl (see table below). If it is desired to express these results rather than direct calculation. Since the dimension 2 x 4 ft. and 1.5 in. are clumsy in metric units.

Object	*Luminance in Footlamberts (Brightness)*		
Black glove on cloudy night	0.0001		
Snow in moonlight	0.015		
Asphalt road—street lighting	0.05		
This sheet of paper lit by a candle	0.75		
Floor brightness in a poorly lighted office	2.0		
Wall brightness in a well-lighted office	50.0		
Luminous ceiling	200		
Asphalt paving—overcast day	400		
North sky	1,000		
Moon, candle flame	1,500	Full color	
Asphalt paving—sunny day	2,000		
Fluorescent tube	2,000		
Kerosene flame	2,500		
Hazy sky or fog	4,500		Human eyes
Snow in sunlight	10,000		Blink or squint
40-w I.F. lamp	15,000		
500-w inside frost incandescent lamp	95,000		
Sun	450,000,000		

Using conversion factors we have:

luminance of the fixture

$$1320 \text{ fl} \times 1.076 = 1420 \text{ ml}$$

luminance of the fluorescent tube

$$\frac{3200}{1.58} \times 1.076 = 2180 \text{ mL}$$

Reviewing, we have established that a source of one candlepower (candela) produces 4 πlumens of luminous flux which produce illumination at the rate of one footcandle (lux) per lumen per sq. ft. (meter). The luminous flux also produces luminance at the rate of one footlambert (millilambert) per lumen transmitted or reflected, per square foot (cm^2). Conversion factors are given in the table below, which for convenience also contains less used. Factors for luminance expressed in candela per unit area.

Lighting-Conversion Factors

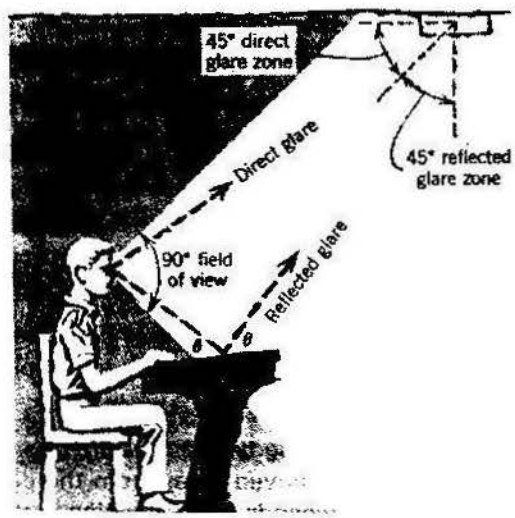
	Multiply	*By*	*To Obtain*
Illumination	**Footcandle**	**10.764**	Lux
	Lux[a]	**0.0929**	**Footcandle**
Luminance	**Footlambert**	**1.076**	**Millilambert**
(Brightness)	**Millilambert**[a]	**0.929**	**Footlambert**
	Footlambert	**0.00221**	**Candela/in.^{2}**
	Candela/in.^{2}	**452.0**	**Footlambert**
Intensity	**Candlepower**	**1.0**	**Candela**[a]

[a]**SI Units.**

Considerations of Lighting Quality

QUALITY of lighting is a term used to describe all the factors in a lighting installation not directly concerned with quantity of illumination. Certainly it is obvious that if a given room is alternatively lighted with a bare bulb and with a luminous ceiling, both giving the same average quantitative illumination (in terms of human output) there is a vast difference in the two lighting systems. This difference is in the quality of the lighting, a term which describes the luminance ratios diffusion uniformity and chromaticity of the lighting. Since uncomfortable brightness ratios, where background luminance exceeds object luminance, are commonly referred to as glare, the quality of the lighting system is also a description of the visual comfort and visual adequacy of the system.

When the discomfort glare is caused by light sources in the field of vision it is known as direct glare. When the glare is caused by reflection of light source in a viewed surface it is known as reflected glare or "veiling reflection."



Glare zones with observer in a head-up position. The direct and reflected glare light paths are delineated on the diagram although reflected glare is usually studied with the eyes down at a reading angle. Placement of fixtures, room size, ceiling height, paint finishes, windows, and so on also affect brightness ratios, and therefore glare.

Direct Glare

Glare by definition produces discomfort and interference with vision. This is a general qualitative statement. To determine whether a specific lighting situation is producing discomfort glare requires a quantitative examination by the factors involved. These factors are brightness, size, position of each light source in the field of vision, plus consideration of surrounding or background brightness. The discomfort effect of a single luminance was determined to be.

$$M = \frac{LQ}{PF^{0.44}}$$

M = individual source glare factor

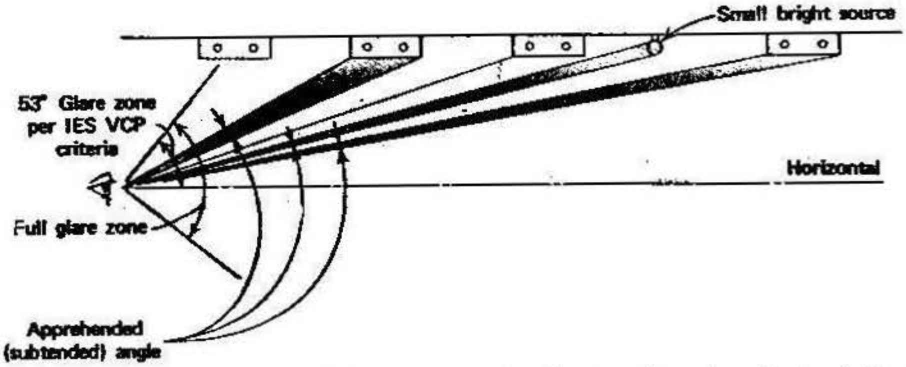
L = apparent source luminance

Q = function of solid angle subtended by the eye when viewing the source

P = position indes factor, relating discomfort to position of the glare source in the field of view

F = room luminance factor, that is, the related eye. Adaptation level.

The formula is a mathematical statement of logical conclusions. Obviously glare is proportional to the source luminance. The size of the source defined with respect to the viewer by the angle subtended by the source at the eye, is the second parameter to which glare is directly proportional (see fig. below)



Glare determination. The glare contribution of each source depends on its size (subtended or apprehended angle), luminance, and location in the field of view. Note that the apprehended angle of a small source is such that even with high brightness it is not objectionable. Such sources are normally called "sparkle." Glare will be much more objectionable with dark background than with a light one; therefore, light-colored paints on ceilings and upper walls are recommended.

It is necessary to consider both these parameters together to understand why a small, very bright source is not a serious problem whereas a large low brightness source, such as a luminous ceiling, may be indeed, a small bright source adds sparkle to the field of vision, and many observers find it pleasant in an otherwise monotonous lighting environment.

The remaining two factors are less self-evident. Glare decreases rapidly as the brightness source is moved away from the direct line of vision and thus, the glare produced by a source depends on its position in the field of view. One way to decrease the detrimental effect of high background brightness was to increase the task brightness. This technique is also effective in reverse with a source of glare, since the amount of discomfort glare produced by a source is inversely proportional to the background or field brightness (also known as eye adaptation level). Thus a ceiling fixture with a luminance of 1200 fL at 65° night easily constitute a source of discomfort glare in space with an eye adaptation level of 50 fL. The same fixture would not be objectionable in a daylight condition, where the eye adaptation level might be 500 fL. (see figure below). A more striking example is that of an automobile's headlights, which at night are so severe a source of glare as to be described as "disabling glare", whereas in daylight, with its concomitant high eye adaptation level, these lights are barely noticeable.

Reflected Glare

(a) NATURE OF THE PROBLEM

The problem of reflected glare is much more complex than that of direct glare because it involves both the source and the task and is inherent in the act of seeing. Vision is produced by light being reflected from the object seen. The object mirrors the source of light in the room

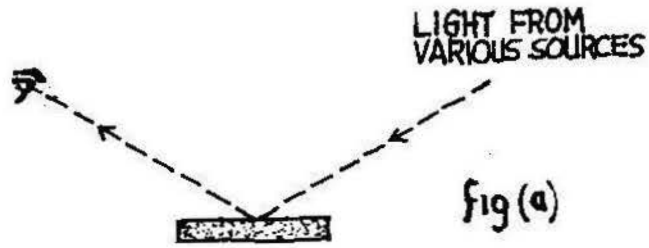


fig (a)

In an interior space there are multiple sources of light. The primary sources are usually one or more lighting fixtures near the observer. Secondary sources are other, more remote fixtures in the room, and all the room surfaces that obtain their light from the primary sources and by reflection become light sources themselves. (see fig. (b) below). To the extent that the primary sources can be mirrored by the vision task glare exists. (we are for the moment ignoring daylight)

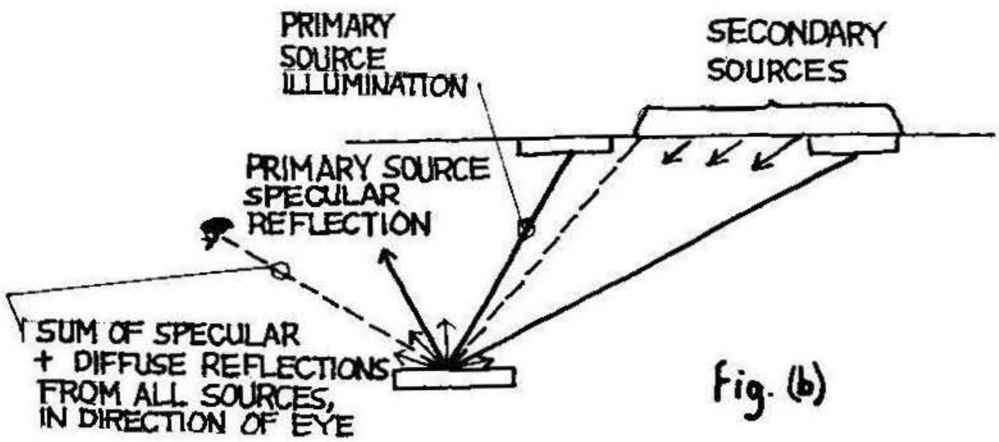


Fig. (b)

Although there is no generally accepted convention with respect to nomenclature, many people refer to reflected glare when dealing with specular (polished or mirror) surfaces and to veiling reflections when considering source reflections in dull or semimatte finish surfaces, which always exhibit some degree of specularity. We use the terms in interchangeable. In all cases the result is a distinct loss of contrast due to the veiling of the image by the reflection of the light source. It is imperative to an understanding of this problem, to appreciate the importance of the nature of the object being viewed, that is, the task. If the object were perfectly absorbent that is, if it had a reflection coefficient of 0%, it would appear completely black as no light would be reflected into the eye.

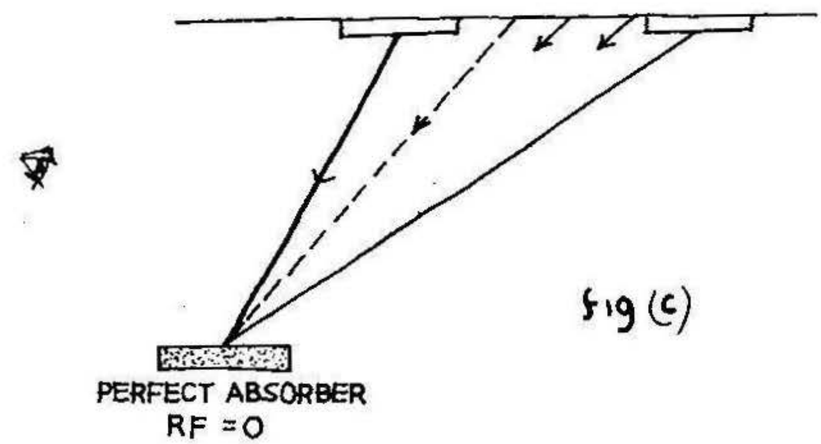


fig (c)

Conversely, if the object were perfectly specular, as a clean mirror, and no light source were within the geometry of reflection, we would not see it (see fig. d). Thus if we took a mirror out on a cloudy night and shined a light on it from over and shoulder, it would be practically invisible since no light would be reflected in the eye.

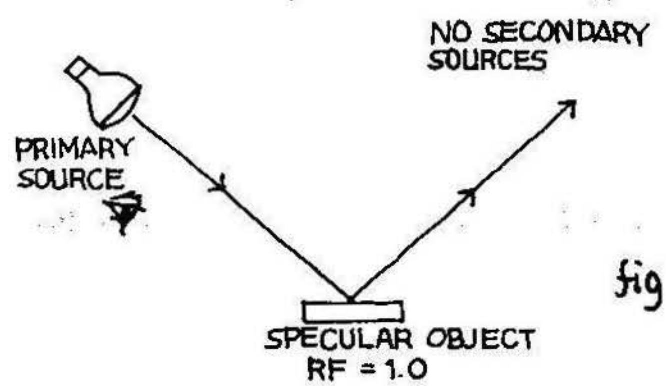
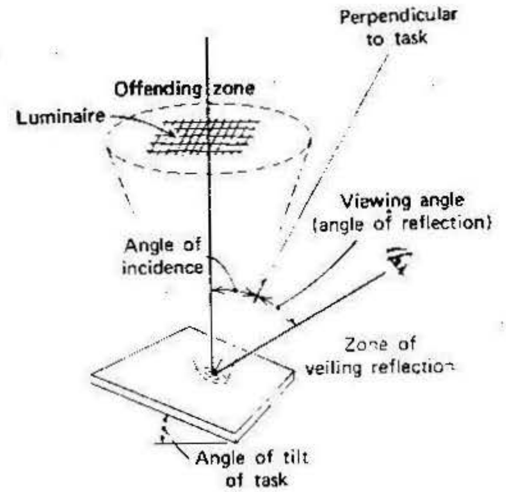


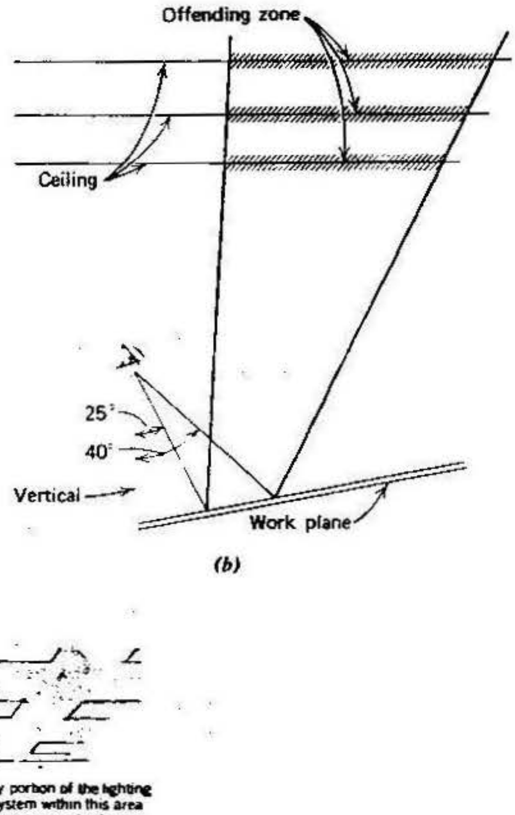
fig (d)

The reader might try this experiment: In an inside space with overhead luminaire, try to examine the surface of a clean mirror. You will find that the best angle to hold it is almost at the angle at which the light source is seen, This is because the mirror is almost completely specular, and it is the slight diffuse reflection near the viewing angle at which permits us to see the surface. If the ceiling is relatively dark, holding the mirror at other angles results in a dark image (ex; of the dark ceiling) and no detail of the mirror surface itself. Thus we understand that reflected glare is due to task surface specularity, whereas object definition (ex; surface detail) is due to task surface diffuseness. As stated above, task contrasts that enable us to see outline, form, silhouette, and so on (as in reading) are diminished to the extent that brightness (sources) are reflected. in the task.

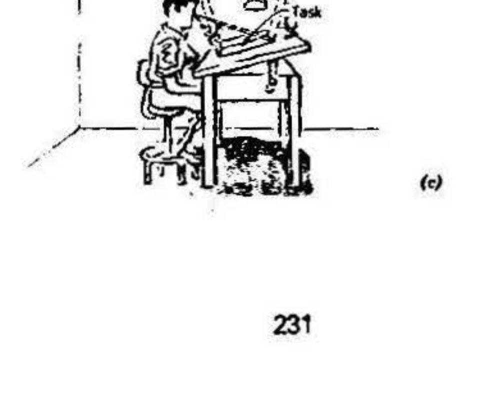
These brightness within the geometry of reflected vision are shown in the figures (a), (b), (c) below and the effects are shown in the next figures (a, b, c, d and e). In studying the geometry of reflected glare in the first figure, it is important to note that a majority of visual work is done in the zone of the 20 to 40° from the vertical, below the eye, bracketing the 25° angle shown.



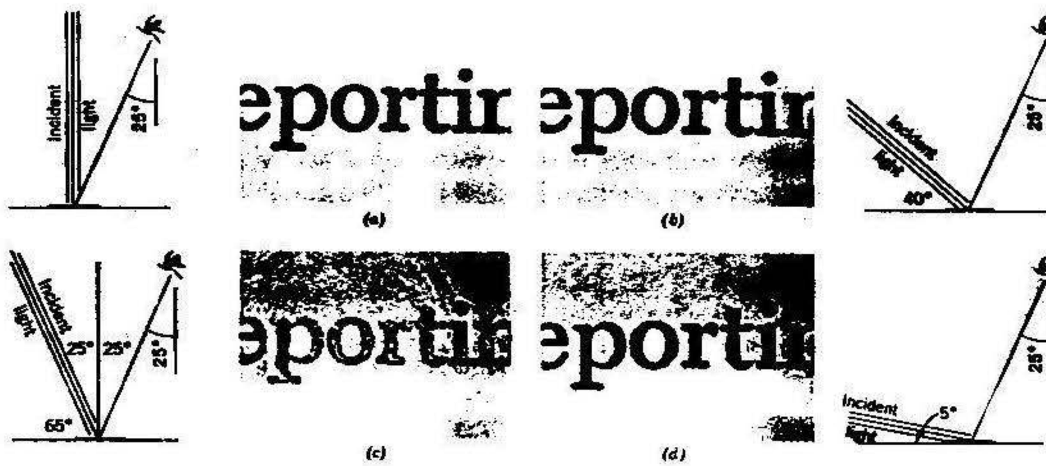
(a)

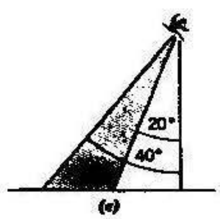


(b)



(c)





Veiling reflection increases the difficulty of the seeing task. In (a), (b), and (d), it is diffuse reflection that permits us to see, since the specular reflection angle does not correspond to the viewing angle except in (c). Veiling is pronounced at the 5° glancing angle even on a matte-finish surface. The normal viewing zone is from 20 to 40°, as shown in (e).

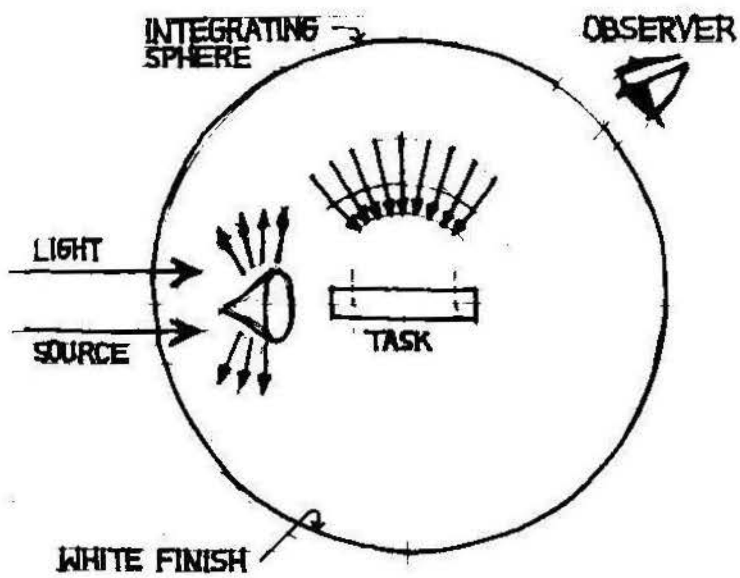
The table below lists a few sample reflectance figures to demonstrate that most materials exhibit both a specular and a diffuse reflectance.

Typical Reflectances

	Reflectance	
Material	*Specular*	*Diffuse*
Matte black paper	0.0005	0.04
Matte white paper	0.0030	0.77
Newspaper	0.0065	0.68
Very glossy white photo paper	0.048	0.83
Metallic paper—copper	0.11	0.28
Dull black ink	0.006	0.045
Super gloss black ink	0.039	0.016

(b) EQUIVALENT SPHERICAL ILLUMINATION (ESI), CONTRAST RENDITION FACTOR (CRF), AND LIGHTING EFFECTIVENESS FACTOR (LEF)

As with direct glare, a scientific approach to the solution of reflected glare problems required a means for accurately defining the loss of contrast due to glare. This requires a reproducible, measurable light quality, that is, a reference lighting system in which seeing ability, which is defined by degree of contrast for a given task, can be measured and to which other lighting systems visability for the same task can be compared. see figure.

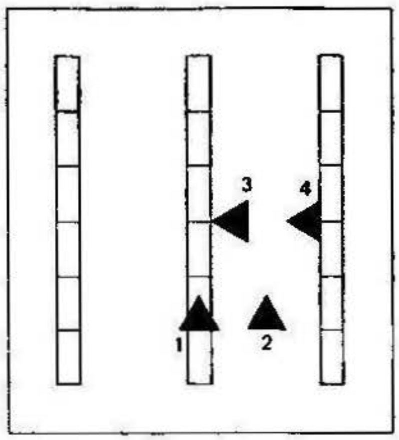


In order to achieve a lighting system almost free of reflected glare, it is necessary to construct an enclosed volume whose surfaces are uniformly reflective and whose primary source is obscured to the maximum extent possible. As illustrated, the integrating sphere is such a device. Light is introduced from the outside, split by a deflector and evenly distributed throughout the sphere by the multiple reflections from the white painted walls. The result is an evenly illuminated volume. When a task is introduced, the illumination falling on it is entirely uniform, that is, there are no high brightness points reflected in it. It is therefore, spherically illuminated. (Note the parallel to sky illumination.) The extent to which any other illumination system can duplicate this glare-free environment is that system's equivalent spherical. illumination (ESI), and is simply the portion of its total illumination that is spherical. Measurement of ESI is accomplished by comparing contrast rendition in the spherical and test systems.

A contrast rendition factor (CRF) of 1.00 would indicate that the system under test gives the same contrast rendition as the integration sphere and that all its illumination is spherical illumination. With a lower CRF, the ESI drops sharply,

The lighting effectiveness factor (LEF) is the ESI footcandles divided by the test illumination in "raw" footcandles, and is therefore a measure of the lighting effectiveness of the total system. A well-known study of school lighting gave the illustrated results for four viewing positions in classroom lighted with ceiling-mounted continuous rows of 2 by 4 ft. (0.60 x 1,120 m.), four lamp, 40 -w fluorescent fixture with lens type wraparound diffusers, on 10 ft. (3.00m) centers.

see figure below.



		Position			
		M1	*M2*	*M3*	*M4*
TI	2L	108	92	125	118
	4L	215	185	250	235
CRF	2L	.75	1.00	.82	1.01
	4L	.76	1.00	.83	1.03
ESI	2L	17.8	91.9	31.5	27.8
	4L	28.4	185.3	58.1	308.3
LEF	2L	.165	1.0	.25	1.08
	4L	.132	1.00	.23	1.31

TI—Task Illumination
2L—2 lamps (inside pair)
4L—4 lamps

Carefully note that:

1. The CRF, and therefore, ESI depends entirely on position and viewing angle, other factors in the space being equal.
2. In an ostensibly very well lighted (215 fc) position (MI), the useful illumination is only 28 fc!
3. The CRF can exceed 1.00 that is, the integrating sphere does not produce perfectly glare-free illumination but only rearly so.

Control of Reflected Glare

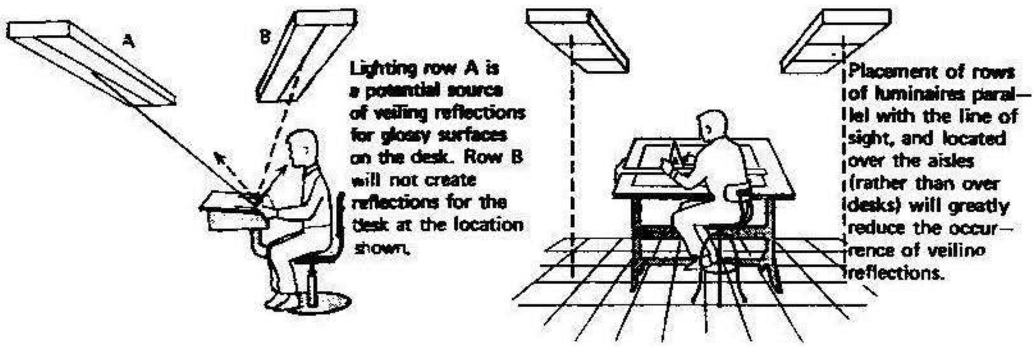
Although there is no known lighting method or material that will completely eliminate veiling reflections, there are number of techniques that will minimize contrast loss due to veiling reflections while maintaining adequate illumination. These are:

* Physical arrangement of sources, task, and observer so that reflected glare is minimal.
* Adjusting brightness (eye adaptation level) so that objectionable brightness is minimized.
* Design of the light source so that it causes minimal reflected glare.
* Changing the task quality.

(a) PHYSICAL ARRANGEMENT OF SYSTEMS ELEMENT.

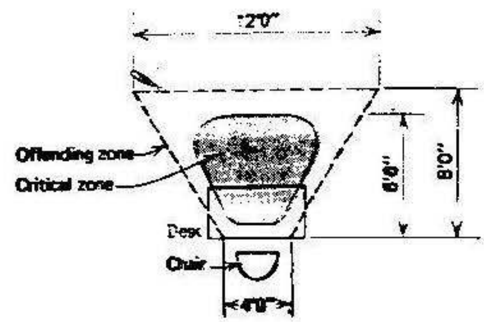
Since reflected glare is caused, as the name states by reflection from a specular surface, the simplest and most effective technique is to arrange the geometry of the system so as to avoid the possibility of reflection. That is, we must remove the source from the offending zone. as in the figure.

Unfortunately, this is only totally effective when a single luminaire is involved and when its replacement with respect to the observer is completely adjustable -a rare combination. In a larger space utilizing multiple sources, particularly in continuous rows, placing the work between rows with the line of sight parallel to the long axis of the units is a very effective technique (see fig. (a) & (b)



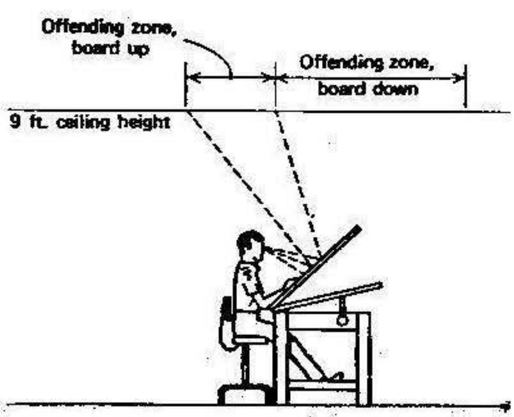
(b)

It is important to remember, however, that the offending zone is also dependent on the tilt of the desk, assuming the work is to be kept flat on it. Thus, for a horizontal 3 x 5 ft. (0.90 x 1.50) standard desk, the offending zone is forward of the desk, as in fig. (a) below.



(a)

With an elevated drafting table the ceiling glare source zone may well be behind the source, as in fig. (b). This being so, it is often possible to reduce glare simply by tilting the work and/or the work surface to such an angle that glare is eliminated.

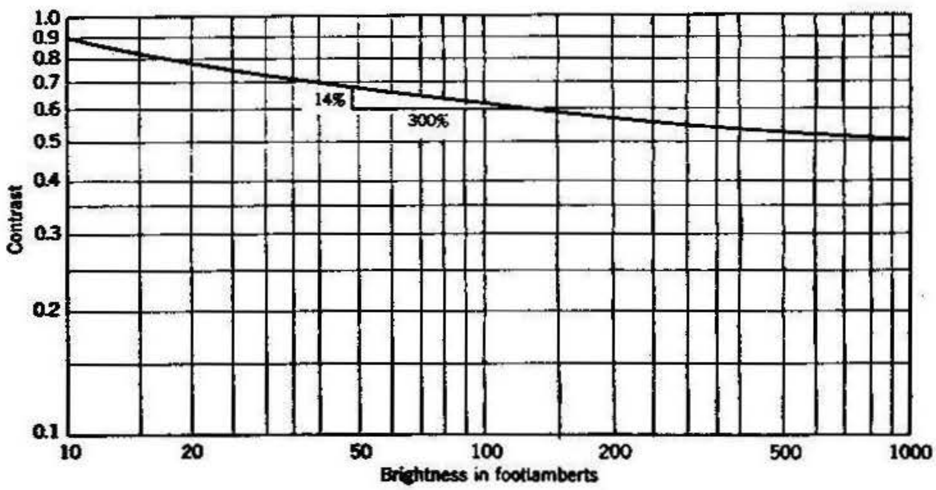


(b)

All of the above geometric solutions pre-suppose a known detailed fixed-furniture layout, a situation that obtains in many but certainly not all cases. In the absence of such data two alternatives are possible: to do a uniform layout and adjust the furniture to it or vice versa. In practice, a combination of both is the most practical approach.

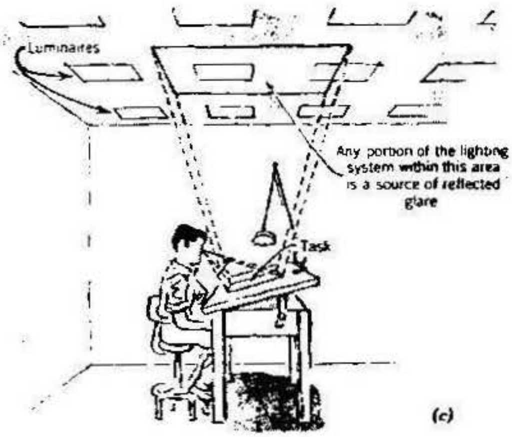
(b) CONTROL OF AREA BRIGHTNESS AND EYE ADAPTATION LEVEL

Loss of contrast can be compensated for (and glare eliminated) by increased overall illumination. We are simply making the task brighter to override the detrimental veiling reflection. The figure below is a curve that quantitatively relates the two parameters.



In the particular instance shown in the curve, a 300% brightness increase is required to compensate for the loss of contrast experienced. This can in many instances, be most practically accomplished not by increasing overall room illumination with the associated extremely high energy consumption but by adding a supplementary source so arranged as to be free of reflected glare. By making this supplementary source position adjustable (as in the figure below) we accomplish three things.

1. Overcome veiling reflection.
2. Provide the high level of illumination needed for exacting task, with minimum energy expenditure.
3. Grant the observer complete control with resultant optimum lamp placement plus psychological satisfaction that will generally prevent worker complaints.

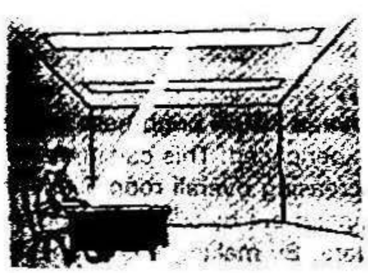


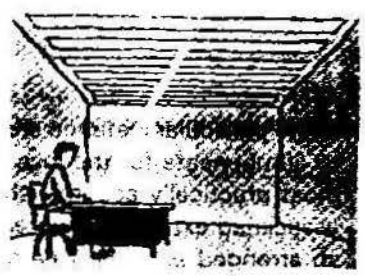
(c)

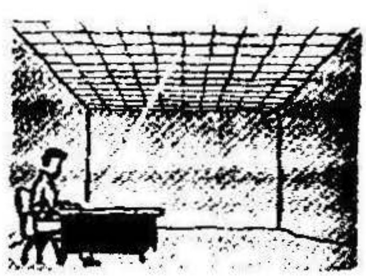
(c) CONTROL OF SOURCE CHARACTERISTICS

The reflected brightness that causes loss of contrast is proportional to the luminaire brightness. It is apparent then that glare may be reduces by reducing the luminaire brightness at the reflection angle. This can be accomplished in four ways.

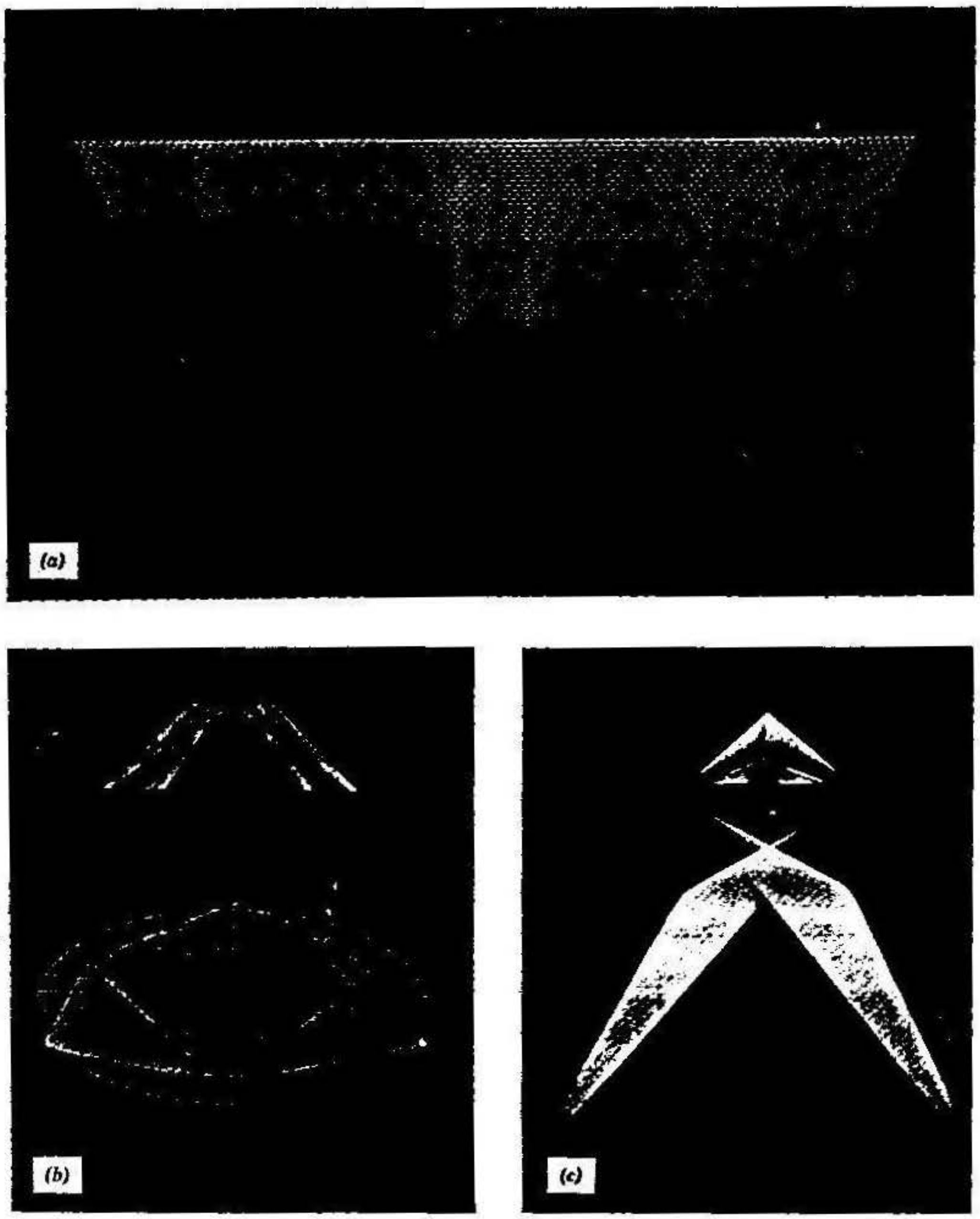
1. Dimming or switching lamps.
2. Using luminaires with lower overall brightness





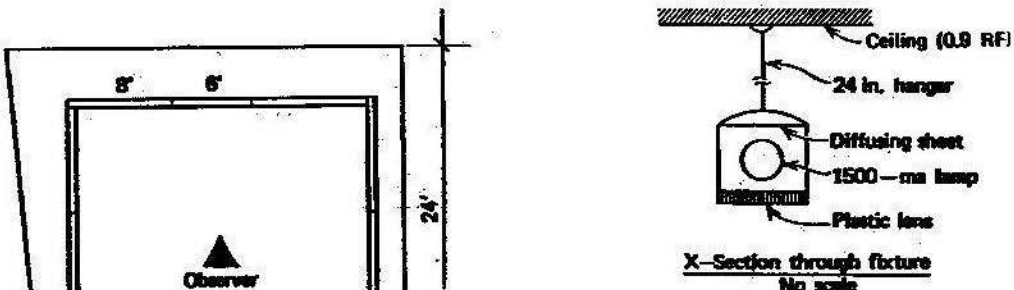


3. Reduce the luminaire brightness only at the offending angles. Diffuser manufacturers designed and row produce a prismatic diffuser whose output 30° and above 60° are diminished, in order to minimize reflected and direct glare, respectively due to characteristics shape of the distribution curve, elements that are so designed are known industrywide as "batwing" diffusers or lenses. If observers can be positioned so that their sight lines are perpendicular to the longitudinal axis of the ceiling fixtures, lenses with linear (side to side) batwing characteristics will perform well. If the observing position varies in aspect with respect to the fixture, a radical batwing curve (in all directions) is required. The figure shows typical batwing distribution curves.

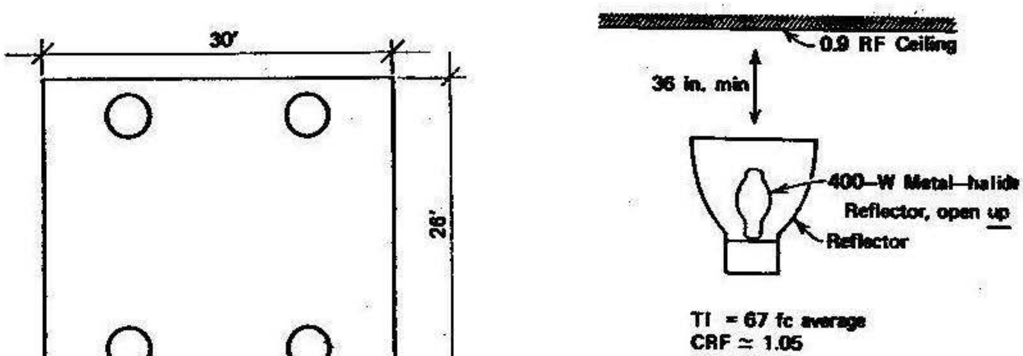


4. Using the luminaire as a primary source to illuminate a large, low-brightness secondary source.

   To overcome the economic disadvantage of multiple low-brightness sources, the ceiling can be used as a secondary source illuminated from high brightness indirect or semiindirect fixtures. These high brightness sources, which can be fluorescent of HID (mercury, metal-halide, sodium), have the additional advantage of high efficacy. The spaces ceiling height must be sufficient to permit suspending the unit at least 18 in. down, to avoid "hot spots" on the ceiling. The minimum suspension length depends on the luminaire characteristics and is normally produced by the manufacturer. To assure high efficiency the ceiling should be painted with a high reflectivity matte white paint, and kept clean. A semiindirect installation using 1500 ma. very-high-output lamps and the results are shown in figure (a) below. Another utilizing 400w indirect metal halide lighting unit is illustrated in figure (b). of extreme importance is the CRF in excess of 1.00 both installation with corresponding high ESI and LEF.



At observer position:
TI = 59 fc
CRF = 1.02
ESI = 68.5 fc
LEF = 1.16

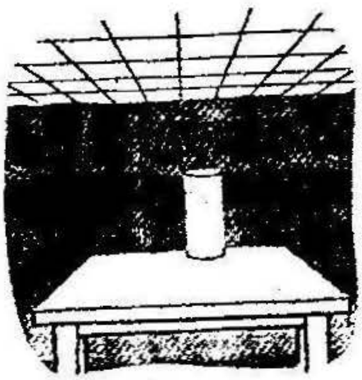


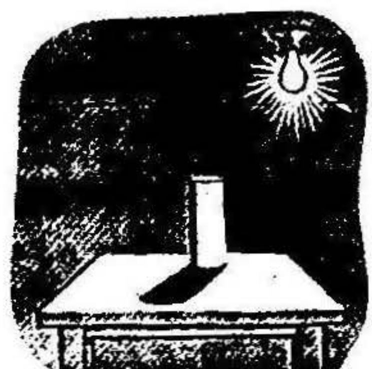
TI = 67 fc average
CRF ≃ 1.05
ESI = 73 fc
LEF = 1.1

Patterns of Luminance

One of the factors of visual acuity is the lighting condition. Its primary factors are (a) Illumination level (b) Disability glare (c) Discomfort glare. Its secondary factors are (d) luminance ratios (e) Brightness patterns and (f) Chromacity.

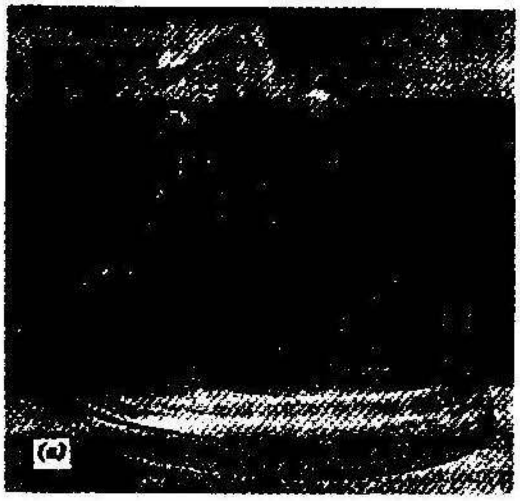
We note among the secondary factors in illumination the existence of "patterns of luminance". This is a way of describing the patterns of light and shadow in a space as they result from the method of illumination in that space. Thus a single source produces sharp shadows while a luminous ceiling or a completely indirect illumination system produces almost completely diffuse light (see figure below). Diffusion is the degree to which light is shadowless and is therefore a function of the number of directions from which light impinges on a particular point and the relative intensities.





There is a widely held but erroneous belief that diffuse lighting is better than directional lighting for all installations. Although this is frequently true for offices, schoolrooms, machine shops, and drafting rooms where shadows would be highly disturbing and could be dangerous (as in the case of a machine shop), it is decidedly not the case where texture must be examined, surface imperfections detected by grazing angle reflections, or in any installation where the flat monotony of diffuse lighting is undesirable. For this reason, some directional lighting is often introduced as an adjunct to diffuse general lighting to lend interest by producing shadows and high brightness variations.

Indeed, as seen in the figures below, directional light is what creates shape and is precisely the characteristics best used to influence architectural space and form.



The section on types of lighting systems, and other sections following, which deal with systems of lighting, illustrate a few of the light/dark patterns produced by different lighting arrangements. The combinations of uplighting and downlighting, perimeter lighting and ceiling are legion; each produces its own shadows and modeling, and each has a quality of its own. It is very much in the interest of the lighting designer to be familiar with these effects so that he or she can mentally visualize them as the design progresses.

Inded it would be well for a designer to prepare a reference sketchbook of such shadow disgrams, It is these patterns of light and darkness that give the ambience and the subject reactions of:

sociability / isolation   clarity / fuzziness

spaciousness / crampedness	simplicity / clutter
formality / informality	boredom / excitement
definition / shapelessness	

Since brightness draw the eye's attention, all the individual brightness sources in the field of view produce an overall impresion. If there is some form or order or pattern to these brightness (as a pattern of lighting fixtures) then the overall of as visually harmonious. If, on the other hand, they are disarray they produce a discordancy precisely as sound produces discordancy in the ear. This visual "noise" is frequently referred to as visual clutter and can be very disturbing. The designer is well advised to keep this important fact in mind. When arranging light sources that are the primary sources of luminance in an enclosed space.

13

LIGHT SOURCES AND THEIR CHARACTERISTICS

LIGHT SOURCES

GENERAL REMARKS

Electrical lighting had its real beginning in about 1870 with the development of commercially usable arc lamps and was given greater impetus nine years later by Edison's first practical incandescent lamp. Todays electric light sources fall into three generic classifications:

(a). The incandescent lamp; including the tungsten-halogen types.

(b). The gaseous discharge lamp, which includes the well-known fluorescent neon, and mercury lamps , plus the more recent metal-halide and sodium lamps; and

(c). The electroluminiscent sources.

The efficiency of a light source is termed its efficacy and is measured in lumens per watt. The table below lists efficacies of modern light sources, including ballast losses where applicable.

Source	*Efficacy (Lumens per Watt)*
Candle	0.1
Oil lamp	0.3
Original Edison lamp	1.4
1910 Edison lamp	4.5
Modern incandescent lamp	14–20
Tungsten halogen lamp	16–20
Fluorescent lamp[a]	50–80
Mercury lamp[a]	30–60
Metal-halide lamp[a]	60–80
High-pressure sodium[a]	90–100
Low-pressure sodium	120–140

In general, efficacy increases with wattage; therefore it is energy-economical to use a small number of higher-wattage lamps than the reverse. It is also usually more economical with respect to fixtures) Since electric lighting in nonresidential buildings consumes 25 to 60% of the electric energy utilized, any attempt to reduce this must necessarily include integration of the cheapest (insofar as energy is concerned), most abundant and, in many ways, most desirable form of lighting available-DAYLIGHT

DAYLIGHTING

Daylighting as a Lighting Design Factor

The provision of lighting in structures has in recent years been considered an amenity rather than a necessity. As such its provision has been the province of architecture rather than lighting design. The reasons for this are clear. Daylight is indeed an amenity. Windows provide visual contact with the outside and the resultant daylight provides a bright, pleasant, airy ambience. When daylight enters through windows (side lighting, as opposed to toplighting), its horizontal directivity provides good modeling shadows, minimal veiling reflections, and excellent vertical surface illumination. Furthermore, the continual variation of daylight which is one of its prominent characteristics, provides a constantly changing pattern of space illumination; one that is unattainable with artificial light. Since these changes are gradual the eyes adapt easily (see luminance) and the effect is one of usual interest. Undoubtedly as a result of these effects, numerous studies have conclusively demonstrated a marked preference for daylight over any other form of lighting.

On the other hand, no ill effects have conclusively been demonstrated to have been caused by lack of daylight, that is, by working in an artificially lighted space. Since an artificial lighting system must be installed in any event to furnish interior illumination during periods when daylight is insufficient. It is now a practice here and in the U.S. of ignoring daylight and even of shutting it out deliberately. Careful design of an electric -lighting system can provide a good visual atmosphere. Further, unlike daylight, control of such systems is relatively simple. Perhaps most important, an interior electric-lighting system has minimal impact of the building architecture, least of all on the all-important building facade. Finally, the energy to power electric lighting systems was cheap.

The option of ignoring daylight in our high-energy-cost and energy resources-poor society is no longer available. That being the case, the designer must learn to cope with special problems that daylight use presents in order to reap its benefits. Since daylight is variable it creates special problems of glare control, direct sunlight control, and heat-gain limitation. In large measure the science (and art) of daylighting is not so much without the attendant undesirable effects. Put otherwise, American & Asian designers must adapt and adopt the British technique of PSALI (Permanent Supplementary Artificial Lighting in Interiors), which is almost universally applied in Europe. This technique which is really a design approach, views artificial lighting as supplementary to daylighting and not vice-versa.

The PSALI technique recognizes that non-residential buildings are principally used during daylight hours and that sufficient daylight is generally available during these hours to provide much of the structures lighting needs. Understood with this statement are the well-founded assumptions that;

(a). The same visual performances can be achieved with less daylight than artificial light, when compared on a footcandle basis.

(b). Current footcandle recommendations can be reduced appreciably without noticeably depreciation of visual performance of most tasks.

(c). Daylight and artificial light can be readily and successfully combined, that is, that artificial light can supplement daylight when the latter is insufficient.

Reference was made above to nonresidential occupancies since residential spaces are also in use during periods of complete absences of daylight, that is, at night. That being so, the artificial lighting system must be designed to furnish all of the required lighting, and therefore PSALI is not applicable. The same is true of course, for other structures that are expected to be in at night.

Since interior daylighting is obviously directly dependent on exterior lighting levels, an understanding of the latter is a clear pre-requisite to designing for the former.

Characteristics of Outdoor Illumination

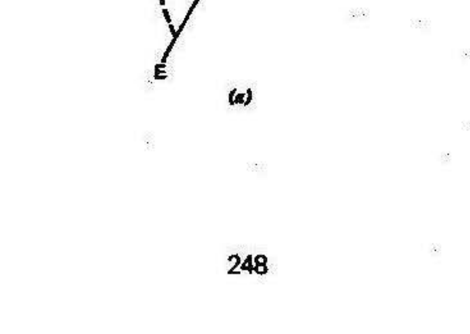
(a) FACTORS

The most prominent characteristic of daylight is its variability. Obviously the source of all daylight is the sun. The level of exterior illumination, at a particular place and time, depends on:

1. Altitude and azimuth (latitude, date, time of day)
2. Weather conditions (cloud, cover, smog)
3. Effects of local terrain (natural and man-made obstructions and reflections).

The position of the sun in the sky is expressed in terms of its altitude above the horizon and its azimuth angle. The latter is defined as its horizontal position angles, measured from the south. Both are normally expressed in degrees. See figure (a)

Light Sources and Their Characteristics

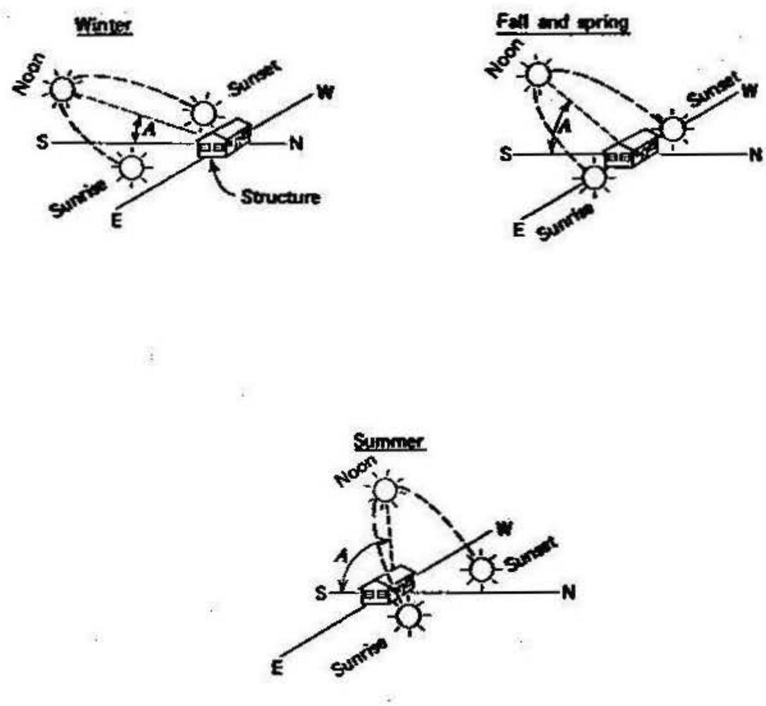


(a)

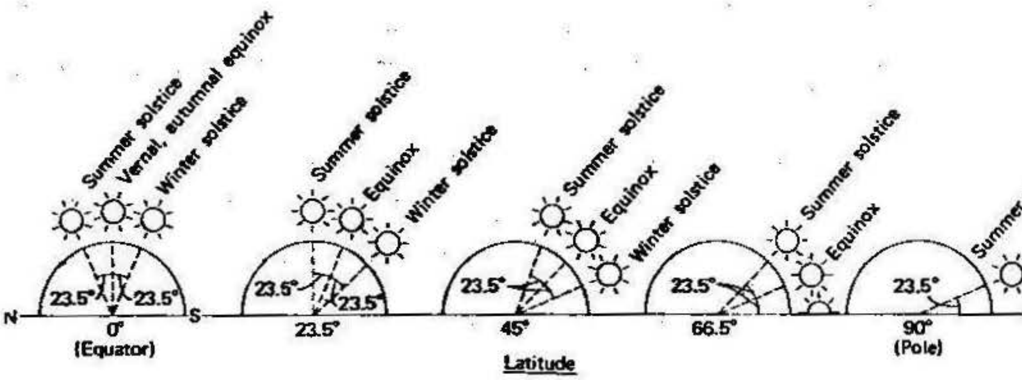
It is assumed that the reader is familiar with the basic astronomical phenomena governing the motion of the earth, which produces seasonal and latitudinal variations in the position of the sun. For our purpose, we will simply state the important facts, which are:

1. For all latitudes, the sun's altitude is highest in summer, lowest in winter or in cold months. Since days are longer in warm months and shorter daylight in cold months, it leads to apparent in rapid motion of the sun across the horizon in the cold months and the apparent slow motion in the summer. Fall and spring (in our case the in-between months are also in between high and low altitude).

(b)



2. As a location approaches the equator (low latitude, either north or south), the sun's daily maximum altitude increases. The seasonal altitude variation, however, is the same for all latitudes (except at those extreme north and south latitudes where the sun is above or below the horizon for extended time periods) See figure (c). This factor not only affects exterior illumination levels but also has a pronounced effect on the design and efficacy of sun-shading devices.



(c)

(a) *The position of the sun is expressed in terms of vertical angle above the horizon (altitude) and horizontal angle, measured from the south (azimuth).* (b) *Approximate position of the sun in each of the seasons, at a midnorthern latitude (approximately 45°). Note that altitude angle is maximum in summer, minimum in winter, and in-between in spring and fall. Note too the length of daylight hours: maximum in summer, minimum in winter, and in-between in spring and fall.* (c) *Maximum sun altitude at various latitudes, for both solstices and equinoxes. Maximum summer sun altitude is 90° minus latitude plus $23\frac{1}{2}$°. Minimum winter sun altitude is 90° minus latitude minus $23\frac{1}{2}$°. Thus for all latitudes the yearly difference between maximum and minimum altitudes is twice $23\frac{1}{2}$°, or 47°, as shown.*

3. The sun's azimuth angle is entirely dictated by the time of day, since the sun by definition transverses the sky between sunrise and sunset,. The principal significance of the building orientation, exposures and shading angles, although obviously the azimuth angle strongly affects exterior illumination levels as can be seen from this table.

Outdoor Brightness, Illumination Levels, and Solar Angles

(a) Equivalent Sky Luminance in Footlamberts—Average Overcast Day

Latitude (°N.)	8 A.M. 4 P.M.	9 A.M. 3 P.M.	10 A.M. 2 P.M.	11 A.M. 1 P.M.	Noon
			December 21		
30	420	740	1020	1210	1270
32	350	700	960	1150	1200
34	320	650	910	1100	1140
36	260	600	840	1020	1070
38	230	550	790	940	1000
40	190	500	740	900	930
42	150	450	660	820	860
44	100	380	600	760	790
46	60	340	550	680	730
48	40	290	470	630	650
50	0	240	420	560	580

March 21 or September 21					
30	910	1320	1710	2010	2140
32	880	1290	1650	1940	2070
34	860	1250	1600	1870	1980
36	840	1220	1560	1800	1900
38	800	1200	1500	1740	1840
40	790	1140	1460	1670	1760
42	760	1120	1410	1600	1690
44	740	1080	1340	1540	1620
46	710	1030	1229	1470	1550
48	690	990	1240	1410	1480
50	650	940	1180	1330	1400
June 21					
30	1270	1730	2250		
32	1280	1730	2240		
34	1290	1730	2220		
36	1290	1730	2200	2960	
38	1290	1720	2160	2840	
40	1290	1700	2120	2650	3060
42	1300	1690	2080	2540	2860
44	1290	1670	2050	2430	2660
46	1290	1640	2010	2330	2520
48	1290	1620	1960	2250	2400
50	1260	1590	1900	2160	2280

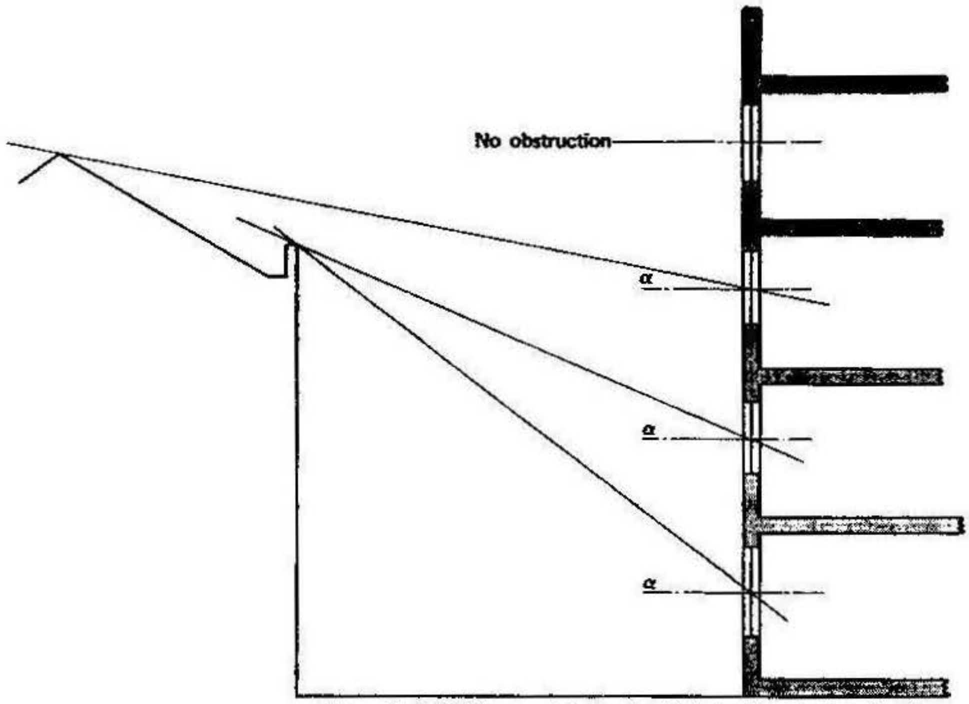
(b) SKY CONDITIONS

In view of the extreme variability of exterior illumination and the difficulty involved in determining it, several fundamental questions face the designer:

1. Should an accurate calculation be attempted, based on a specific location, or should prevailing weather and its attendant sky conditions be used?
2. The sun's values of exterior illumination should be used in calculating interior levels in view of the daily and seasonal changes?
3. What degree of accuracy is necessary?

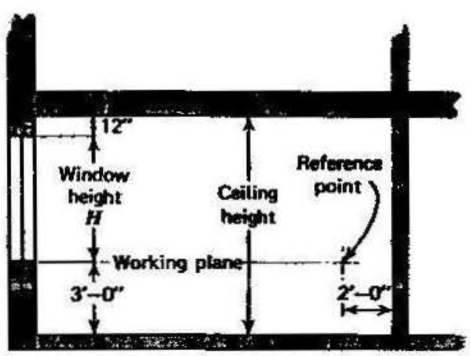
When using hand methods (as opposed to computers), it is not practical to calculate hourly, daily, or even monthly variations. It is sufficient to establish four basic sky conditions, which can then be used with the specific design approach desired these are:

1. Completely overcast sky
2. Clear sky, without sun
3. Clear sky, with sun
4. Partly cloudy sky



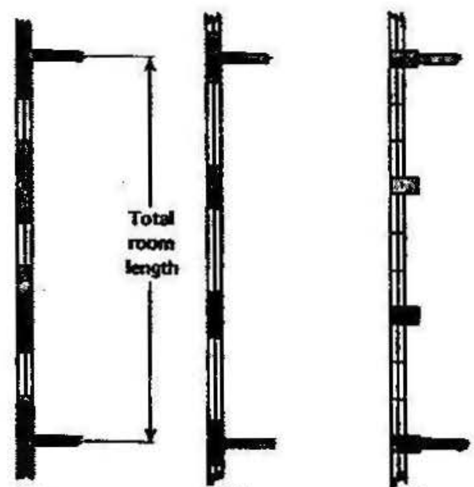
External obstructions and the angle of obstruction. The angle of obstruction α is measured from the center of the window to the outline of the opposite building. See Figure 19.12

(a)



Section through a unilaterally lit room showing the assumed dimensions. These dimensions are the same for bilateral lighting except that the reference point is midway between the window walls.

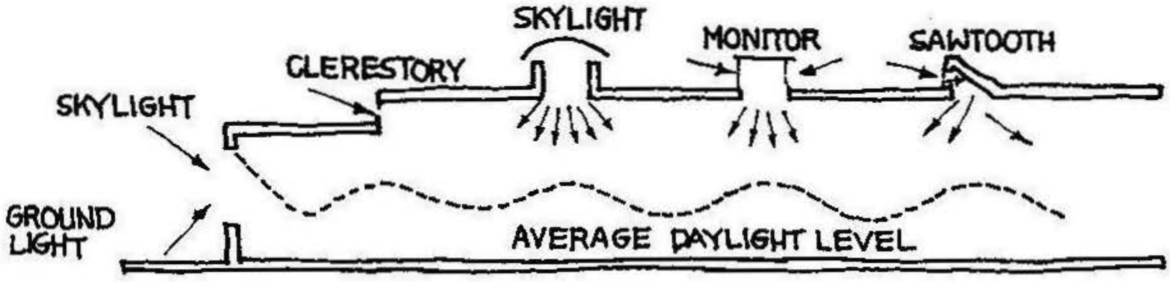
(b)



Plans of window walls showing window width expressed as a percentage of total room length.

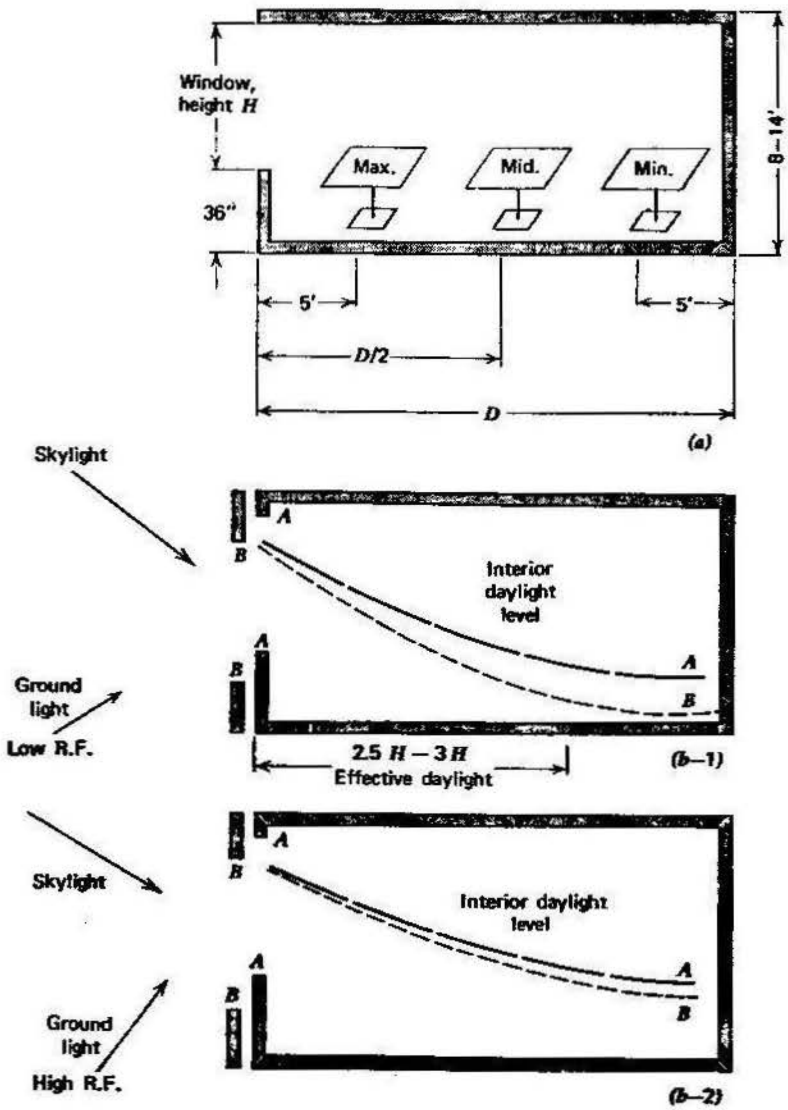
(c)

Sketches indicating the parameters of the CIE calculation systems. (a) Indicates how obstruction angle α is calculated. (b) Shows a vertical section through a room with dimensional data relevant to this system. (c) Indicates how size (length) of windows is calculated with respect to overall room length.

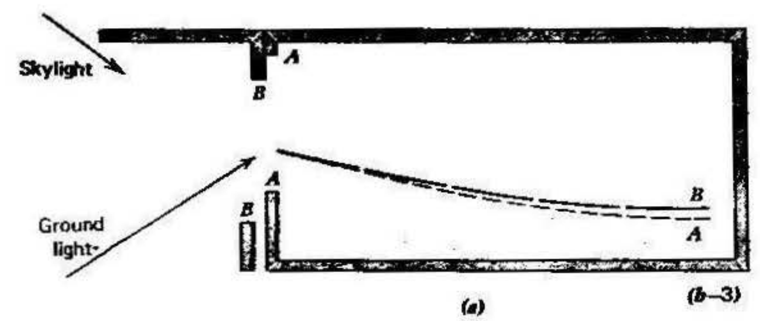


(c)

(a) *Standard room section for which IES daylight calculation method applies. Window is assumed to extend from a 36-in.-high sill to the ceiling. Daylight is caluclated for three points in the room along a line from the center of the window to the center of the back wall. These points are indicated as Max., Mid., Min. and are 5 ft from the window, at depth midpoint, and 5 ft from the back wall.* D *represents room depth from window to back wall. Room height from 8 to 14 ft can be accomodated.*



(b) *These two figures, (b-1) and (b-2), show the effect of window design with varying illumination conditions. In both figures window height is the same, except that design* A *carries the window to the ceiling and design* B *has the window head 18 to 24 in. below the ceiling. In diagram (b-1) skylight represents the major portion of incoming daylight; this results in a rapid drop in daylight penetration and a large difference between conditions* A *and* B. *In diagram (b-2) reflected ground light, resulting from a high-reflectance surface outside the window, comprises a large portion (30–50%) of the incoming light. Since ground light is rereflected from the ceiling into the depth of the room, the result is higher daylight levels within the room, particularly at the back, and only a small difference between the interior daylight levels for window designs* A *and* B.

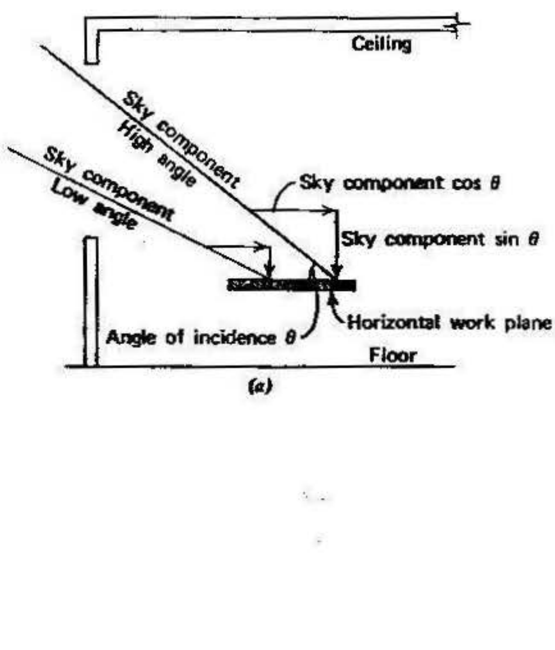


Effective daylight can be expected to a depth of 2½ to 3 times window height. Diagram (b-3) represents a design where direct skylight is blocked by an overhand resulting in interior daylight being principally rereflected ground light. Here a lower sill height (B) *results in better penetration.*

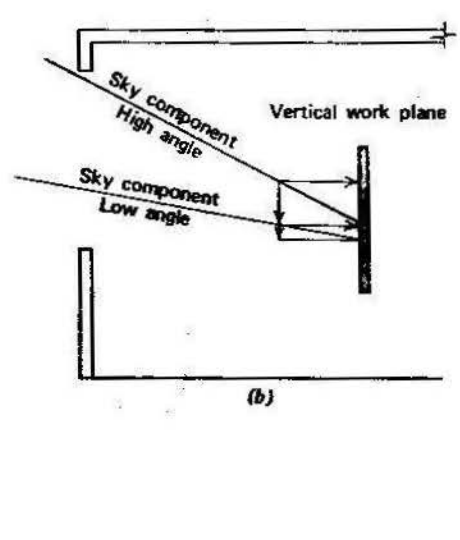
Factors in Interior Daylighting

(a) HORIZONTAL and VERTICAL SURFACES

Since the sky component of daylight enters side fenestration at an angle, it can be resolved into horizontal and vertical components, as shown in this figure.



(a)



(b)

The vertical component that illuminates horizontal surfaces is proportional to the sine of the angle of incidence, and the horizontal component that illuminates vertical surface is proportional to the cosine of this angle. Therefore, for horizontal tasks, windows should be as high as possible, and for vertical tasks, as low as possible. Since most tasks are horizontal, tall narrow windows will give better, deeper, penetration than short wide windows of the same area.

(b) WINDOWS DETAILS

The effect of window construction on total fenestration area reduction is often neglected even windows with narrow mullions and light metal frames have 8 to 10% obstruction, heavy window supports and small glass, lights can result proportional daylight reduction. Further obstruction readily results from dust accumulation, wired glass, and mechanical system items such as pipes and ducts inside the room, adjacent to windows.

(c) SURFACE REFLECTIONS

Interior reflections are very important in daylight design. In addition to determining the magnitude of the internally reflected light component (IRC) within the room, they determine in large measure the eye adaption level. A high adaptation level is desirable to avoid a sensation of glare when the window and its immediate surround are in the field of vision. Furthermore, the internally reflected light component contributes largely to the diffuseness of the room light. With low IRC the sky component of daylight is the essential illuminant, and diffuseness and the room penetration are reduced floors receive the sky component and should have at least 20 % reflectance. Walls receive reflected light. Since they are the surfaces seen at normal vision angles, they are responsible for eye adaptation levels and should have at least 50% reflectance.

Exterior surface reflection can provide the deep daylight penetration that is required for effective daylighting. Thus a concrete or lightpainted provide surface (RF of 50 to 70%) will furnish ¼ to 2/3 of the light incident on a windows depending on shading and orientation. When combined with a high-reflectance ceiling, optimal interior distribution is achieved.

(d) GLARE AND HEAT CONTROL

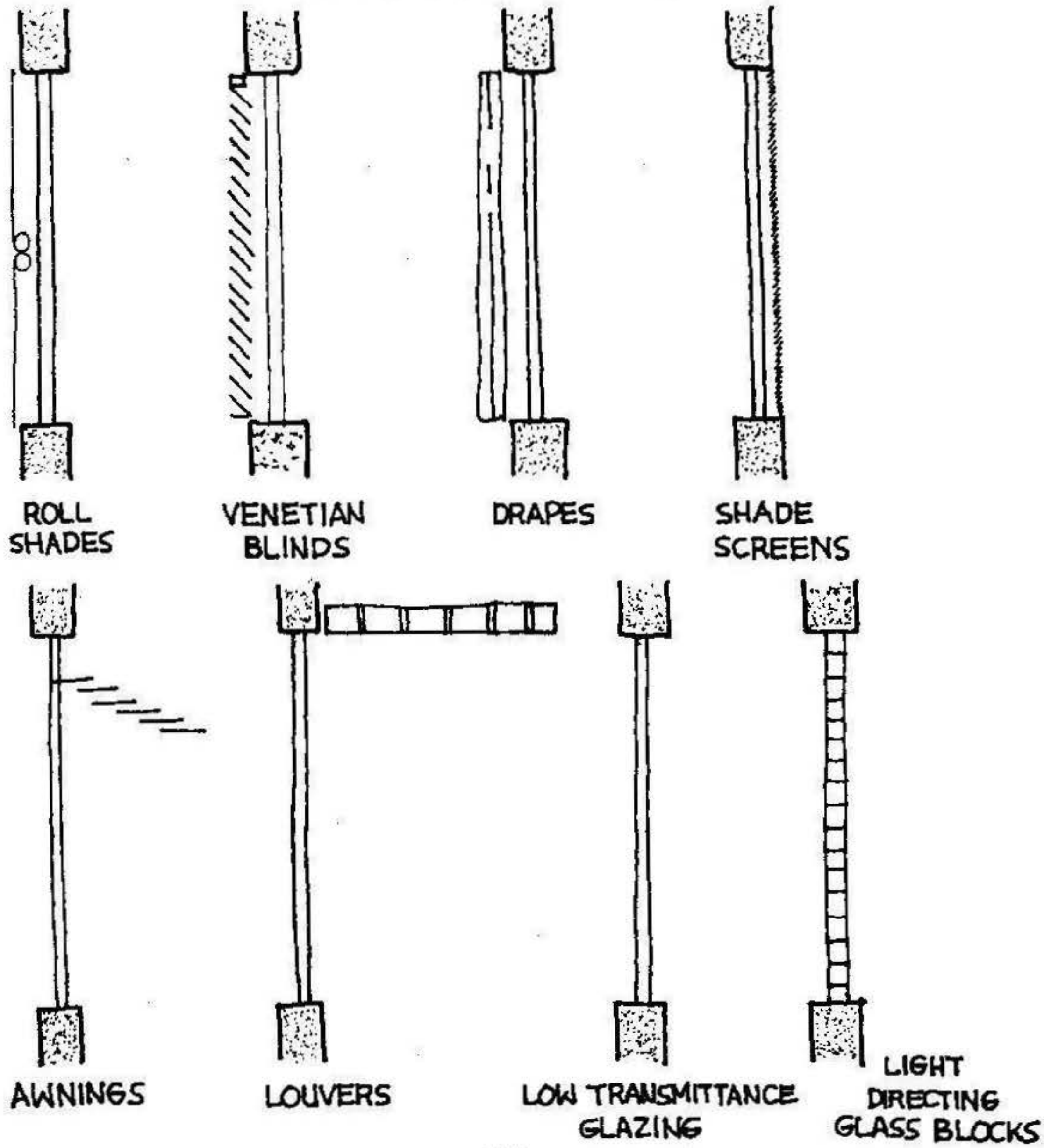
These are among the most difficult problems to overcome in daylighting. The following recommendations will be helpful:

1. Provide high-reflectance surfaces particularly toward the back of the room where daylight factor is low.
2. Building orientation is the factor that determines which areas are exposed to natural glare end heat extremes. Bear these facts in mind
   - (a). Southern exposure receives maximum overall daylight but without the extremes associated with low sun angles, except at a high latitudes.

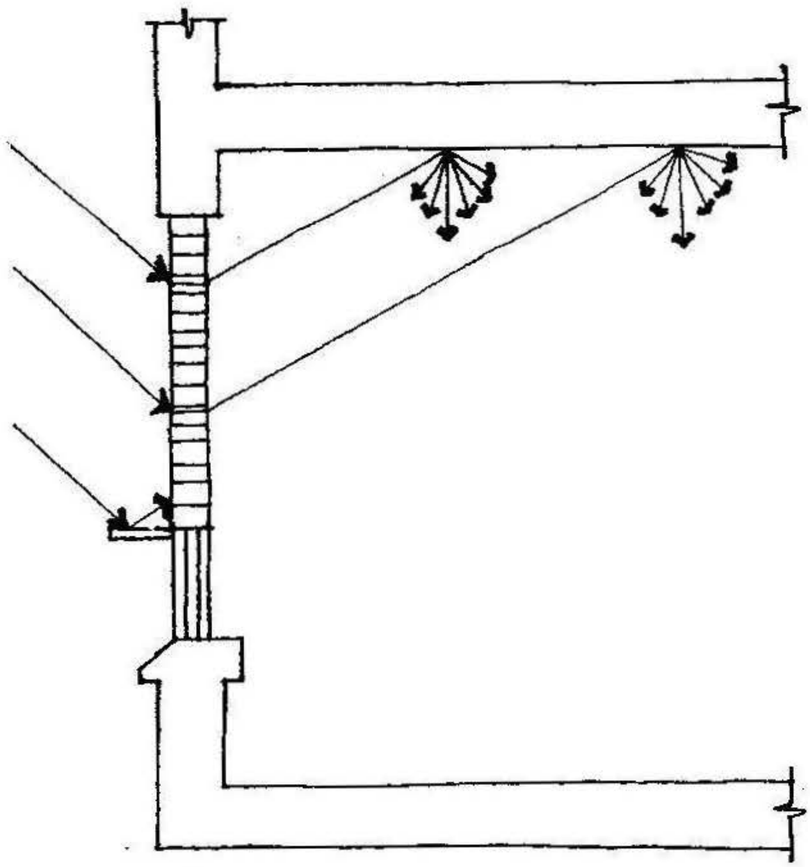
(b). Northern exposure receive minimum daylight and no direct sun. As a result levels are low but relatively constant throughout the day.

(c). East and west exposures receive extremes of light and heat because of low sun angles in early morning and late afternoon. Heat build-up on west exposure in very cold months can be almost as severe as summer because of the low sun angle. Furthermore, the low sun angle in the very cold months (winter) makes the sun's relative motion appear extremely rapid, necessitating, either a fixed a sun control device, or one that is easily and rapidly adjustable.

3. Provide fixed sunshades on sun exposures at low altitudes; and operable sun control devices on sun exposures at all latitudes. A few of the common types are shown in the figure below. Vertical devices are effective for low sun angles horezontal at high sun angles. The latter are also useful to reflect incoming skylight onto the ceiling.



4. Translucent, limited-brightness, glass or plastic fenestration including light-directing glass block just below the ceiling line and above the vision panels (clear windows) provides maximum penetration and minimum glare.

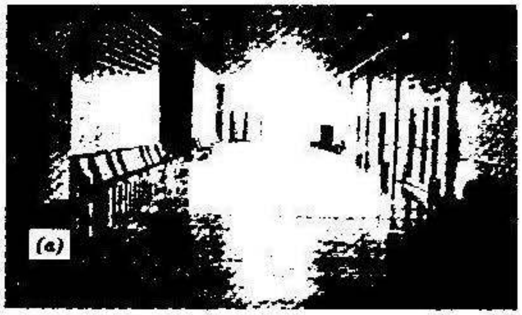


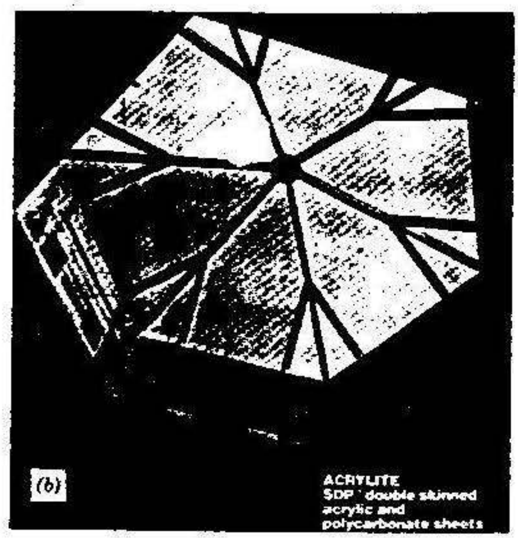
5. Tinted windows and heat-reflective films are not usually desirable, except in retrofit installations, because they affect the quality of daylight. (the day/night appearance of the structures is also affected. During daylight hours vision out is possible and vision in is blocked. The reverse is true at night)

6. Orient furniture so that daylight comes from the left side or the rear of the line of sight. Never face a window except one northern exposure and no exterior glare sources in the line of sight.

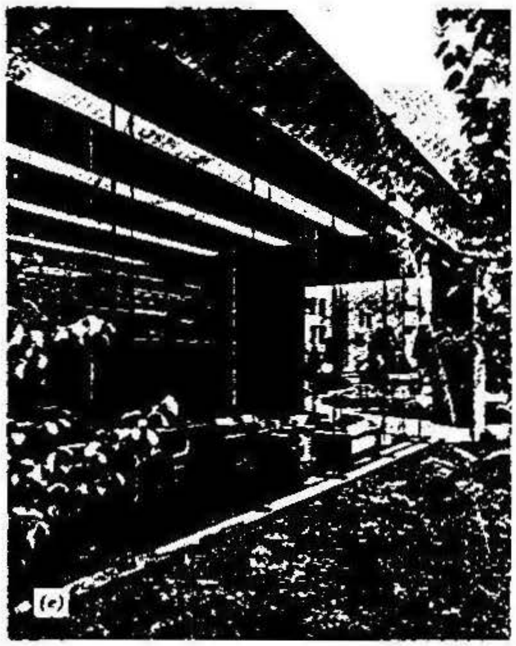
7. Sunlight reflection from adjacent structures can be a source of intense glare and heat. Orientation, vegetation, and fixed shading are possible solutions to this problem.

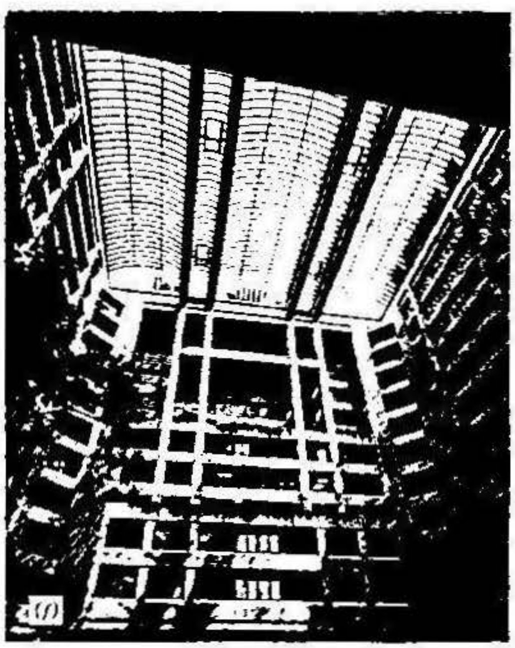
Some of the principles involved in the use of daylight in construction.



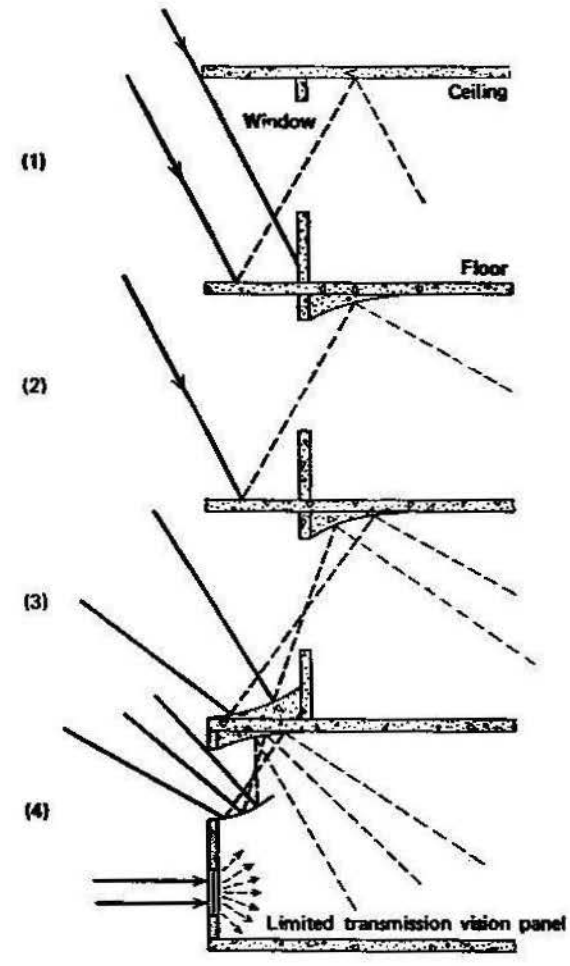



(d)


(e)


(f)

For Energy Conservation, wall and ceiling designs that admit daylight without excessive attendant heat gain and direct glare are most desirable. These rely principally on utilizing reflected daylight.



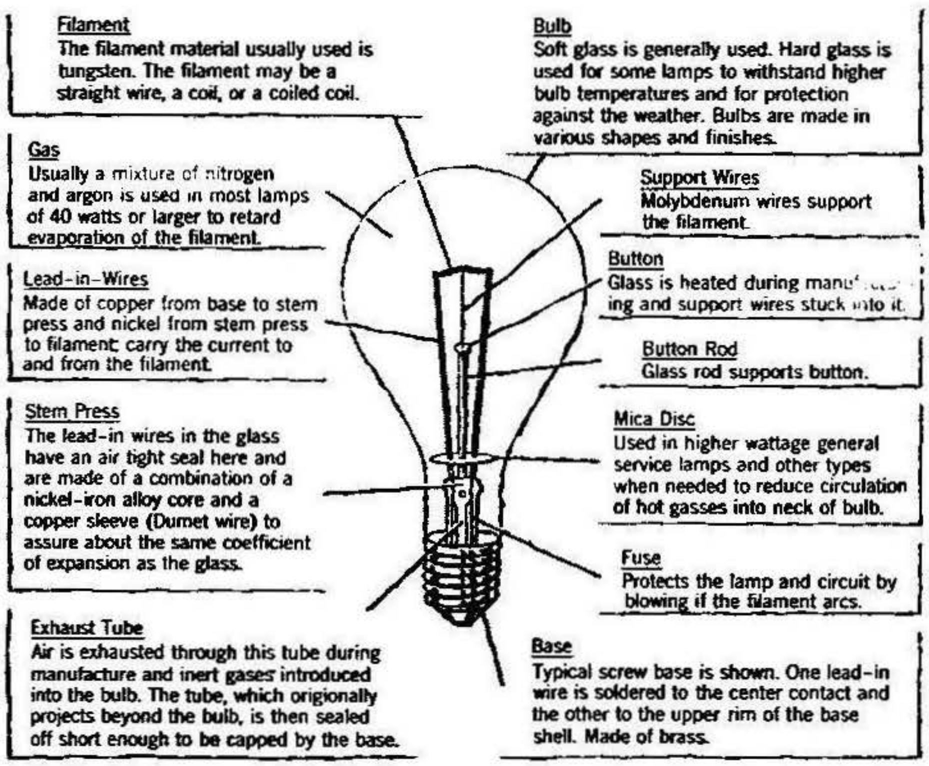
(g)

INCANDESCENT LAMPS

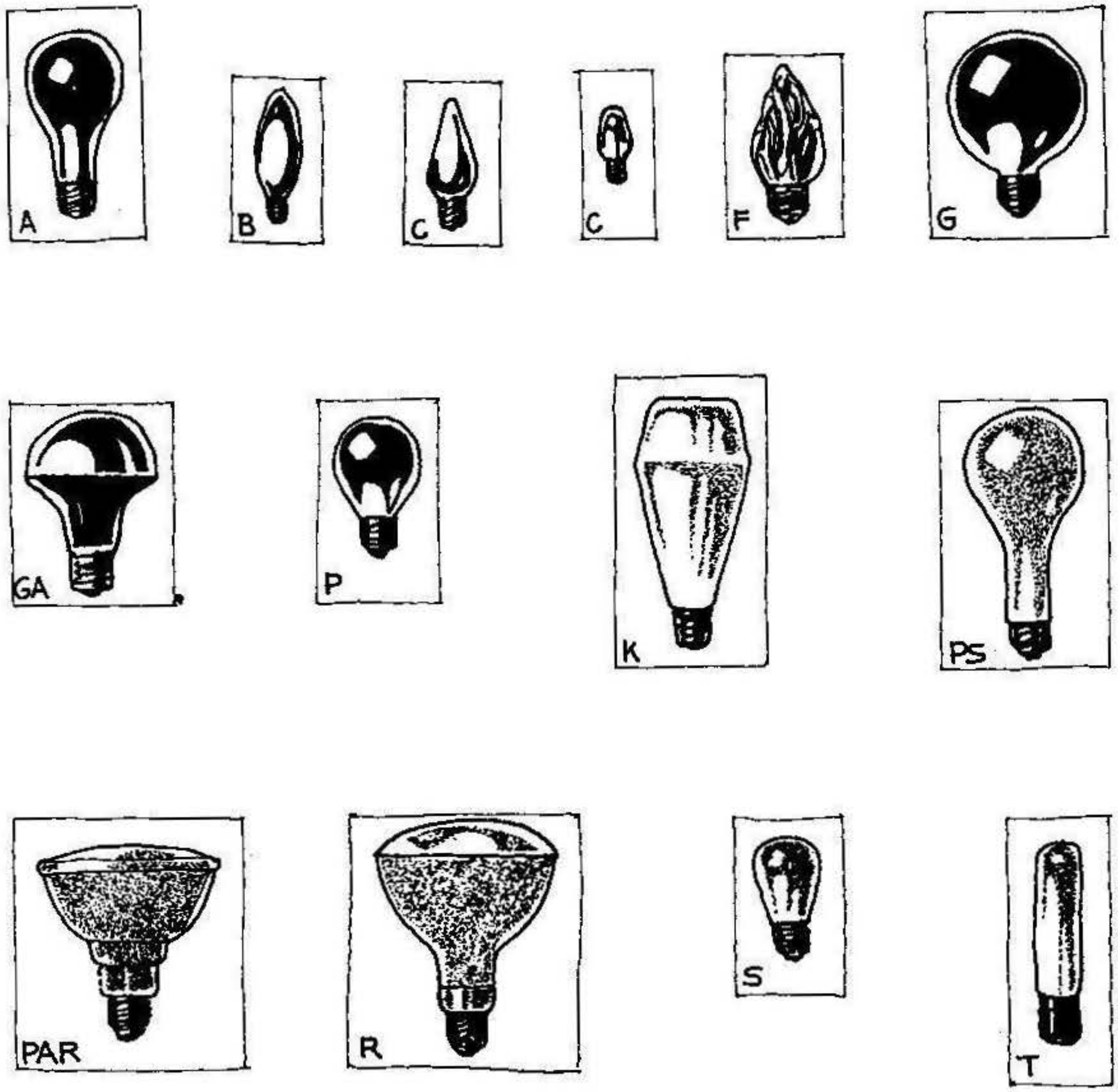
The Incandescent Filament Lamp

(a) Construction

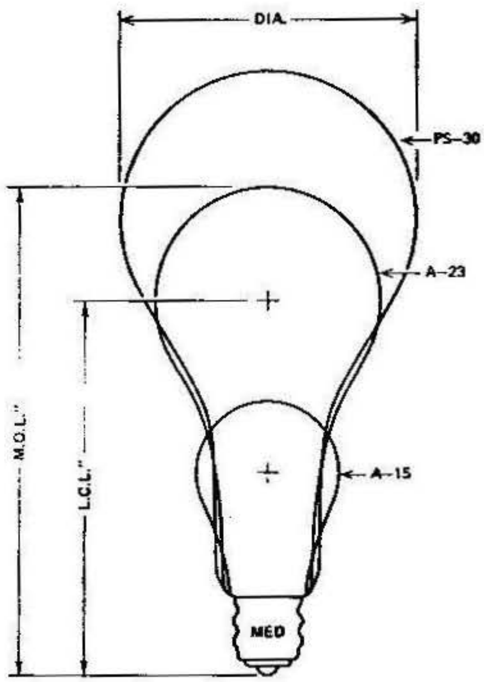
This lamp consists simply of a tungsten filament inside a gas-filled, sealed glass envelope as shown in the figure below. Current passing through the high-resistance filament heats it to incandescence, producing light. Gradual evaporation of the filament causes the familiar blackening of the bulbs and eventual filament rupture and lamp failure.



Incandescent lamps are available in many bulb and base types and special designs for particular application. See figure below.



A - STANDARD SHAPE
B, F - FLAME SHAPE
C - CONE SHAPE
G - GLOBE
GA - COMBINATION OF G AND A
P - PEAR SHAPE
K - ARBITRARY DESIGNATION
PS - PEAR SHAPE STRAIGHT NECK
PAR - PARABOLIC ALUMINIZED REFLECTOR
R - REFLECTOR
S - STRAIGHT
T - TUBULAR



BULB DIAMETER IS GIVEN IN 1/8 INCH. EXAMPLE: AN A-19 BULB HAS A DIAMETER OF 19/8 INCH OR 2 3/8".

M.O.L.–MAXIMUM OVERALL LENGTH: THIS FIGURE REFERS TO THE MAXIMUM LENGTH OF THE BULB.

L.C.L.–LIGHT CENTER LENGTH: THIS DIMENSION, IMPORTANT WHEN DESIGNING REFLECTORS, IS MEASURED FROM THE FILAMENT TO A POINT THAT VARIES WITH BASE TYPE. SEE FIG' 14.14.

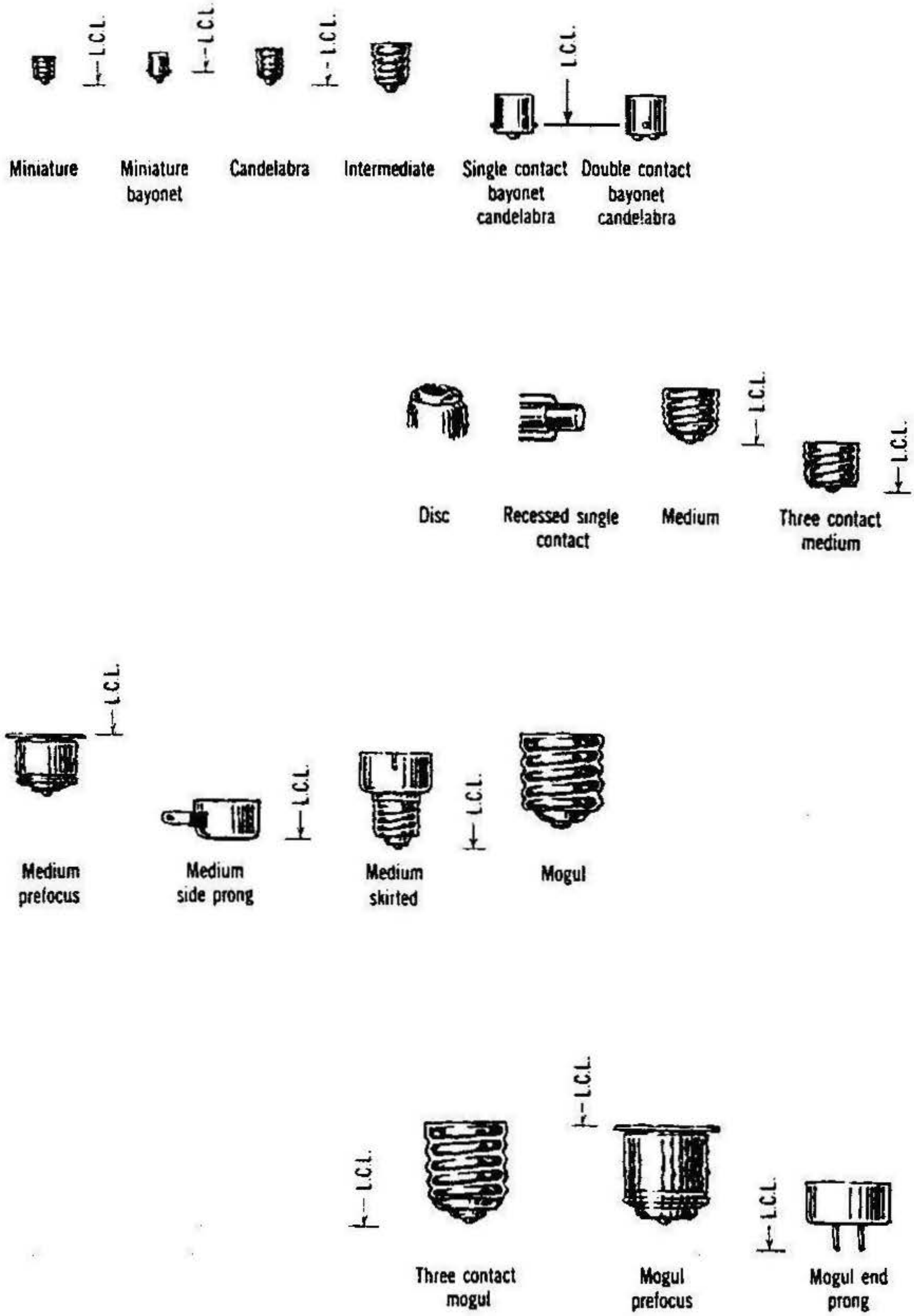
LAMPS SHOWN AT SLIGHTLY LESS THAN ½ ACTUAL SIZE

	A – STANDARD SHAPE									PS – PEAR SHAPE							
WATTS	15	25	40	60	75	100	100	150	150	150	200	300	300	500	750	1000	1500
BULB	A-15	A-19₁	A-19₂	A-19₃	A-19₃	A-19₃	A-21₁	A-21₁	A-23	PS-25	PS-30	PS-30	PS-35	PS-40	PS-52	PS-52	PS-52
DIAMETER"	1 7/8	2 3/8	2 3/8	2 3/8	2 3/8	2 3/8	2 5/8	2 5/8	2 7/8	3 1/8	3 3/4	3 3/4	4 3/8	5	6 1/2	6 1/2	6 1/2
M.O.L."	3 1/2	3 7/8	4 1/4	4 7/16	4 7/16	4 7/16	5 1/4	5 1/4	6 3/16	6 15/16	8 1/16	8 1/16	9 3/8	9 3/4	13	13	13
L.C.L."	2 3/8	2 1/2	2 15/16	3 1/8	3 1/8	3 1/8	3 7/8	4	4 5/8	5 3/16	6	6	7	7	9 1/2	9 1/2	9 1/2
BASE	MED	MED	MED	MED	MED	MED	MED	MED	MED	MED	MED	MED	MOG	MOG	MOG	MOG	MOG
STANDARD FINISH	IF	IF	IF W	IF	IF	IF	IF	IF	CL IF	CL IF	IF	IF	IF	IF	CL IF	CL IF	CL IF

CL – CLEAR IF – INSIDE FROSTED

To diffuse the light, most bulbs are either etched on the inside (inside-frosted) or are coated inside with white silica. The silica coating provides almost complete light diffusion at a cost of approximately 2 to 3% of the light output, whereas inside-frosted bulbs provide only partial diffusion but do not reduce light output. Inside-frosted bulbs are normally supplied for general service use unless other types are specified. Colored lights also readily available from either coated bulbs or bulbs of colored glass.

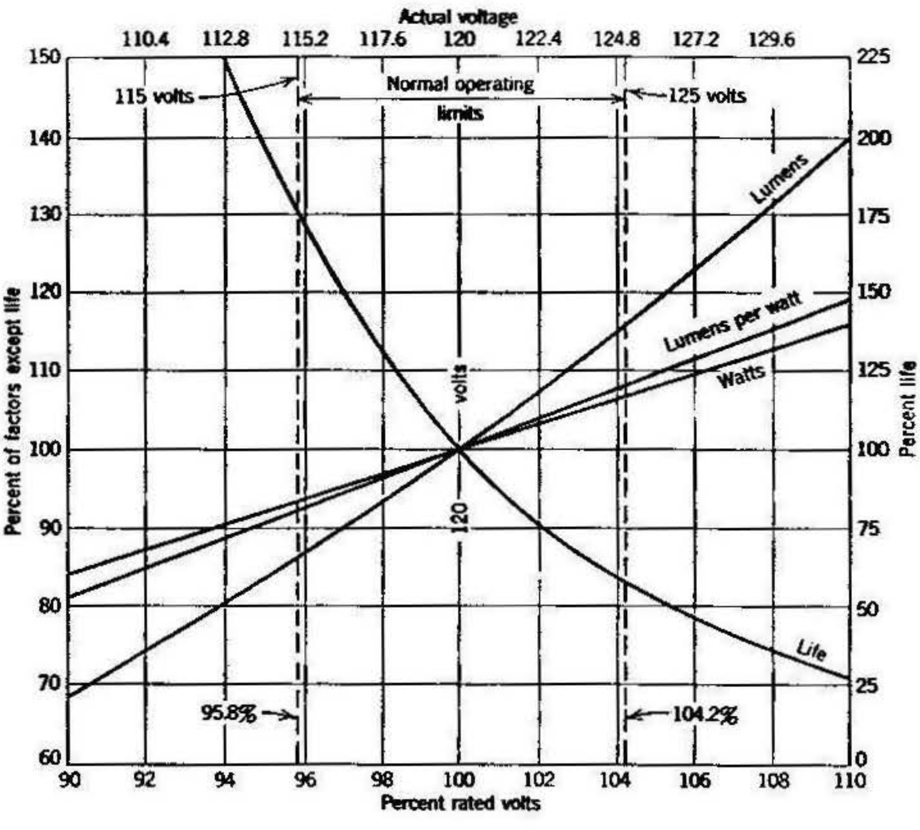
The lamp base is the means by which connection is made to the socket and thereby to the source of electric current. Most lamps are made with screw bases of various sizes, the most common being the medium screw base. General service lamps, of 300 W and larger, use the mogul screw base. Where exact positioning of the filament is important, as it is when lamps are placed in precise reflectors on in lens systems, a screw base cannot be used. Lamps designed for such use are furnished with one of the special bases illustrated.



Bases shown at approx. 1/4 actual size

(b) Operating Characteristics

These are critically dependent on the voltage at the lamps; therefore the life, output, and efficiency of a lamp can be markedly altered by even a small change in operating voltage, as illustrated by this figure:



For example, burning a 120-V lamp at 125V (104.2%) means approximately:

16%	more light (lumens)
7%	more power consumption (watts)
8%	higher efficacy (lumens per watt)
42%	less life (hours)

Burning a 120V lamp at 115V (95.8%) means approximately:

15%	less light (lumens)
7%	less power consumption (watts)
8%	lower efficacy (lumens per watt)
72%	more life (hours)

Particular note should be taken of the effect of voltage on lamp life. In installations where lamp replacement is difficult and/or expensive, lamps may be burned slightly under voltage and life prolonged, thereby decreasing the frequency of replacement. However, since efficiency is decreased by this procedure and since energy cost is normally a major cost in any lighting installation over the life of the installation, a detailed cost analysis should be made by the consulting engineer involved. Conversely, where lamps are replaced before burnout on a group replacement system and initial installation cost per footcandle and/or energy costs are high, lamps may be burned over-voltage, thereby increasing output and efficiency by shortening life.

This procedure is normal in sportslighting installations because of the high cost of tower-mounted floodlights, making it mandatory to extract the maximum light for each unit. In stadium installations that have yearly burning schedules averaging less than 200 hours, 10% overvoltage operation doubles the light output but still allows a once-year, off-season relamping and is therefore a highly economical procedure.

In general, however, it is advisable to generate incandescent lamps at rated voltage, accepting balanced efficiency, output, and life.

(c) Other Characteristics

1. Lumen Maintenance. Light output decreases slowly with lamp life as the bulb blackens. Position during burning and bulb temperature affect this characteristic.

2. Color. White, with large, yellow-red component and therefore highly flattering to the skin. Since color depends on temperature, high-voltage lamps are bluer, low-wattage lamps are yellower. Dimmed lamps give yellow-red light.

3. Surroundings. Generally impervious to external heat, cold, or humidity. Starting completely unaffected.

4. Lamp Efficiency. Since incandescent lamps produce light as a by-product of heat, they are inherently inefficient. Efficiency increases with wattage, varying from 8% for a 25W lamp to 13% for a 1000-W unit. This increased efficiency can

also be noted from the lumen output figures in the table below. Thus a 100-W lamp produces the same 1750 lm as two 60-W lamps, representing 20% increase in efficacy.

Typical Incandescent Lamp Data (Listing a Few of Many Sizes and Types of 115-, 120-, and 125-v Lamps)

Watts and Life		*Approx. Color Temp. (K)*	*Lumens*		*Physical Data*		*Description*
Lamp Watts[a]	*Average Rated Life (Hours)*		*Initial Lumens*	*Lumens per Watt*	*Shape of Bulb*[b]	*Base*	
6 Cl	1500	2370	58	9.7	S-6	Cand.	Indicator
6	1500	2370	40	6.7	S-14	Med.	—
7½ Cl	1400	—	45	6.0	S-11	Med.	—
10 Cl	1000	—	115	11.5	S-14	Med.	Sign
15	2500	—	126	8.4	A-15	Med.	—
15	1000	—	120	8.0	A-17	Med.	—
15 Cer	400	—	138	9.2	S-11	Med.	Refrigerator
15	1000	—	115	7.7	T-7	Cand.	Appliance
25	1000	—	228	9.1	A-17	Med.	Rough service
25	1000	2550	357	14.3	A-19	Med.	—
25	1000	—	238	9.5	A-19	Med.	Vibration service
25 Cl	1000	—	242	9.7	T-6½	Inter.	Showcase
40	1000	2770	452	11.3	A-15	Med.	Appliance
40	1500	—	460	11.5	A-19	Med.	—
40 SW	1500	—	445	11.1	A-19	Med.	—
40	1500	—	—	—	G-25	Med.	Decorative
50 W	1000	2790	830	16.6	A-21	Med.	—
60	1000	2800	890	14.8	A-19	Med.	—
60	2500	—	760	12.7	A-19	Med.	Long life
60	1000	—	575	9.6	A-19	Med.	Rough surface
75	750	—	1210	16.1	A-19	Med.	—
75 SW	750	—	1180	15.7	A-19	Med.	—
100	750	2870	1740	17.4	A-19	Med.	—
100	750	—	1690	16.9	A-21	Med.	—
100	2500	—	1460	14.6	A-19	Med.	Long life
100	1000	—	1220	12.2	A-21	Med.	Rough surface
150	750	2900	2810	18.7	A-21	Med.	—
150	750	—	2580	17.2	PS-25	Med.	—
200	750	2930	3940	19.7	A-23	Med.	—
200 SBIF	1000	—	3320	16.6	PS-30	Med.	—
300	750	2940	6000	20.0	PS-30	Med.	—
300	1000	—	6000	20.0	PS-30	Mogul	—

[a]Figures in this column designate the input watts, and the letters identify the treatment of the glass bulb; thus: 60 means 60 w. All inside frosted unless otherwise noted. Other letters have these meanings: W, white; SBIF, silver bowl, inside frosted; Cl, clear; SW, soft white; Cer, ceramic.

[b]*Bulb Designations.* Bulb designations consist of a letter to indicate its shape and a figure to indicate the approximate maximum diameter in eighths of an inch

(d) Summary

The principal advantages of incandescent lamps are low cost, instant start and restart, simple inexpensive dimming, simple compact installation requiring no accessories, cheap fixtures, focusable as a point source, as a point source, high power factor, life independent of number of starts, and good color.

The principal disadvantages are low efficacy, short lamp life, and critical voltage sensitivity. Low efficacy results in a large number of fixtures, high maintenance costs, and large heat gain. Short lamp life results in high replacement labor cost. Voltage sensitivity requires careful and expensive circuit design. Also, light concentration at the filament (point source) requires careful fixture design in order to avoid glare and, if undesirable, sharp shadows. Because of the poor energy characteristic, incandescent lamp use should be limited to the following applications:

1. Infrequent or short duration use
2. Where low-cost dimming is required
3. Where the point source characteristic of the lamp is important, as in focussing fixtures
4. Where minimum initial cost is essential

A brief list of conventional incandescent lamps and their physical and operating characteristics is given in the table on page 278. Lamp data for use in the design should be taken from current manufacturer's literature. Data presented here are typical.

Special Incandescent Lamps Including Tungsten-Halogen

1. *Rough service and vibrations* lamps are built to withstand rough handling and continuous vibration, respectively, both of which conditions are extremely hard on general service lamp filaments. Neither type is intended for general use, and both types have lower efficacy than a general service lamp (see table above)

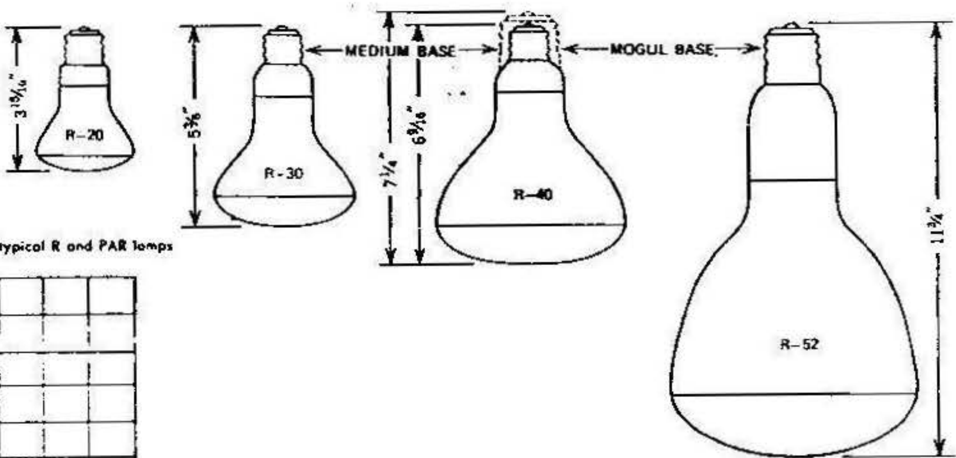
2. *Extended service lamps* are designed for 2500-hr life and are useful, as mentioned, in locations where maintenance is irregular and/or relamping is difficult. The lamp is really designed for slightly higher voltage than that at which it is applied, and therefore efficacy is reduced. (as shown in the table and the figure earlier on operating characteristics of a standard 120-V)

   So called "Long-Life" lamps, which are guaranteed to burn for two, three, or five years, are lamps designed for much higher voltages than that at which they operate. Since they normally sell at a high cost and are very inefficient, their use is seldom advisable. In a cost comparison made of three lamps with 750, 2500, and 10,000-hr lives, respectively, including cost of lamps, energy and relamping, the relative costs per million lumen hours were 1.0, 0.94, and 1.17, respectively.

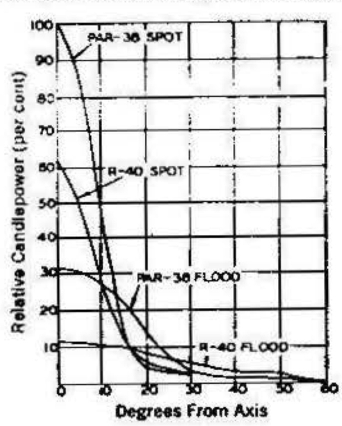
(a) REFLECTOR LAMPS.

These are made in "R" and "PAR" shapes (see previous illustrations on bulb shapes) and contain a reflective coating on the inside of the glass envelope; this gives the entire lamp accurate light beam control. Both types are available in narrow or wide beam design, commonly called spot and flood, respectively. R lamps are generally made in soft glass envelopes for indoor use, whereas PAR lamps are hard glass, suitable for exterior application. Also available is a lamp with an elliptical reflector bulb shape. This causes the beam to focus a few inches in front of the lamp, permitting high-efficiency application in pinhole downlights or deep baffle units where use of ordinary R lamps causes trapping and loss of the most of the lamp's output. This elliptical reflector action in a fixture is illustrated in this figure.

Typical reflector lamp dimensional and photometric data given in this figure.

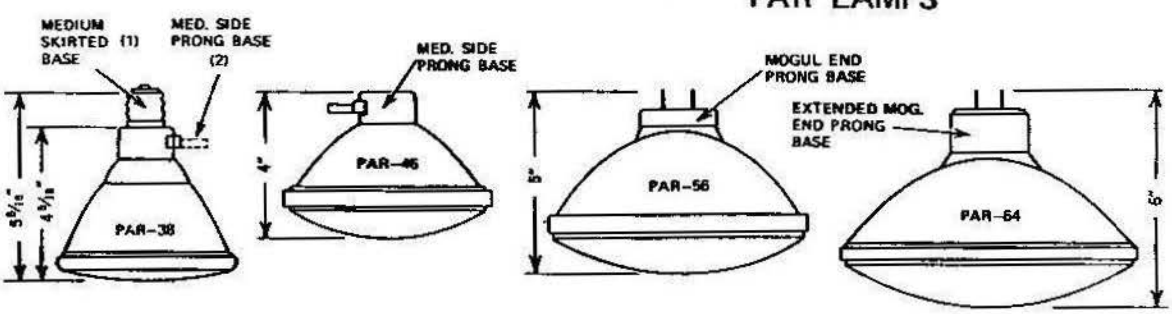


Candlepower distribution of typical R and PAR lamps



R LAMPS

PAR LAMPS



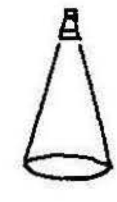
Approximate Initial Output of Typical PAR and R Lamps

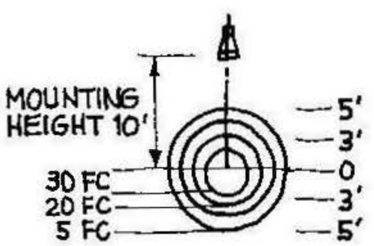
Wattage	Bulb	SPOT LAMPS				FLOOD LAMPS			
		Central Candle-power	Beam Spread (1)	Beam Lumens	Total Lumens	Central Candle-power	Beam Spread (1)	Beam* Lumens	Total Lumens
75	R-30	1,850 (2)	50°	430	860	415 (2)	78°	610	860
150	R-40	7,400 (2)	20°	910	1,950	1,100 (2)	110°	1,530	1,950
300	R-40	13,500 (3)	35°	1,660	3,700	2,200 (2)	115°	3,250	3,700
500	R-40	22,000 (3)	60°	4,240	6,500	4,700 (2)	120°	5,930	6,500
500	R-52	—	—	—	—	—	—	—	7,850
750	R-52	—	—	—	—	—	—	—	13,000
150	PAR-38	9,100 (3)	30°	960	1,730	3,500 (2)	60°	1,220	1,730
200	PAR-46	36,000 (3, 4)	17° x 23°	1,200	2,250	10,500 (2, 5)	20° x 40°	1,300	2,250
300	PAR-56	70,000 (3, 4)	15° x 20°	1,800	3,840	24,000 (2, 5)	20° x 35°	2,000	3,840
300	PAR-56	—	—	—	—	10,000 (2, 6)	30° x 60°	2,100	3,840
500	PAR-64	104,000 (3, 4)	13° x 20°	3,000	6,500	35,000 (2, 5)	20° x 35°	3,400	6,500
500	PAR-64	—	—	—	—	11,000 (2, 6)	35° x 65°	3,500	6,500

(1) To 10% (approx.) of maximum candlepower. (2) Average in 10° cone. (3) Average in 5° cone. (4) Narrow spot.
(5) Medium flood. (6) Wide flood. *Estimated. All lamps have 2000 hour life.

Illumination patterns resulting from typical PAR **spot and flood lamps** are shown in this figure below. When using R and PAR lamps the fixture acts principally as a lampholder, since beam control is built into the lamp.

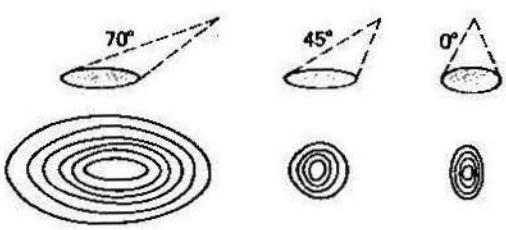
The beam of the PAR lamp is cone–like in shape. Each type of PAR lamp has a distinct illumination pattern which varies in size and light intensity – depending on the angle at which the lamp is aimed and on its distance from the area illuminated.



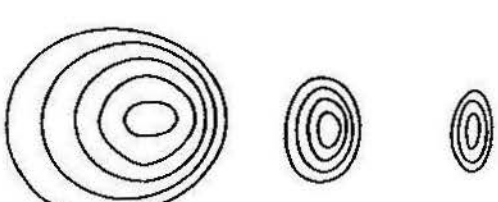


150 WATT PAR 38 FLOOD

When centered directly on the surface to be lighted (at right angles or zero degrees) the small PAR 38 sizes give a round lighting pattern. The concentric rings show the amount of light measured in footcandles at various distances from the beam center. The round lighting pattern changes to oval or elliptical when the lamp is aimed at an angle.



300 WATT PAR 56 NARROW SPOT



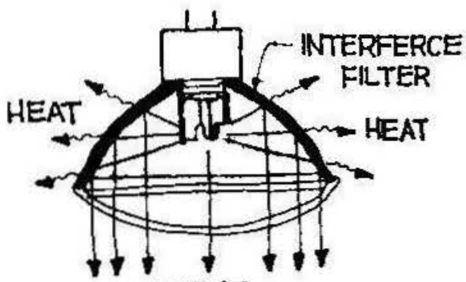
300 WATT PAR 56 MEDIUM FLOOD

The lighting pattern of the larger PAR 46, 56, and 64 lamps is oval or elliptical, whether centered directly on the surface or aimed at an angle. As shown in the two diagrams, aiming PAR lamps at progressively greater angles – proportionately increases both the length and width of the area illuminated. In general, for spotlights the length of the lighting pattern becomes proportionately greater – and in the case of floodlights, the width.

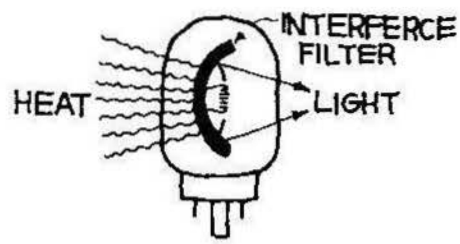
(b) INTERFERENCE (DICHROIC) FILTERS.

Since filters had been previously used only in specialized applications such as projection lamps to remove heat from the light beam, are now available in PAR lamps. The basic filter is a thin film that operates on the interference principle rather than absorption. Thus the surface remains relatively cool.

In one design that is utilized to limit the heat in the light beam, the film is applied to the inside back of the lamp. It acts by transmitting infrared heat out of the lamp back while reflecting light out the lamp front. (see figure below). Typical applications are now window displays, over food counters, and in any location where a "cool beam" is desirable. Of course, provision must be made for removal of the heat from fixture if the lamp is housed.



(a)



(b)

In a second design, multiple-layer filters are applied to the front of the lamp. Each film acts to transmit one color and reflect its complement (two color, hence dichroic). These dichroic filter lamps produce a purer, more saturated color at high efficacy than is possible with selective absorption filters.

(c) LOW-VOLTAGE LAMPS.

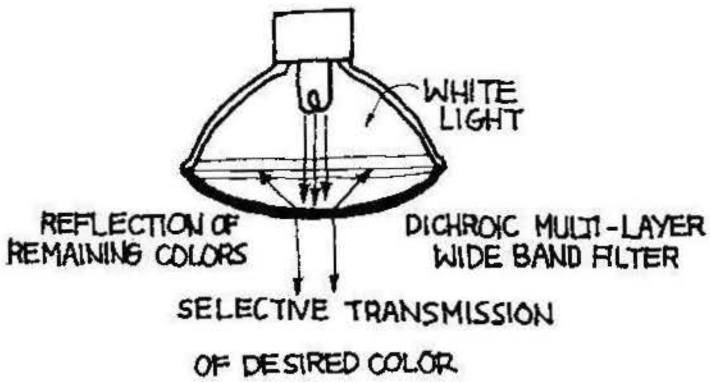
These lamps, in PAR shape and for 6-V operation, are available in extremely narrow beam spread (5-10°) for special precision control floodlighting. The low voltage makes their application to exterior work simplier.

(d) KRYPTON GAS

This gas in lamps in place of the usual nitrogen-argon mixture conducts heat more slowly from the filament and results in the approximately 10% higher efficacy, longer life, and a smaller envelope. The cost premium for krypton lamps is approximately 50%. Applications are in long-life lamps to increase efficacy and in exterior spots and floods to increase life and output.

(e) ENERGY-SAVING LAMPS

These are basically long-life lamps that are filled with krypton to raise efficacy. These lamps can be substituted for standard lamps for appreciable savings in energy costs and relamping costs. (see table below). Note that efficacy is still considerably below that of a standard lamp. The use of krypton-filled lamps increases initial cost and decreases energy cost.



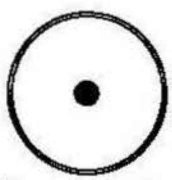
(f) TUNGSTEN-HALOGEN (QUARTZ) LAMP

This is a "gas filled tungsten incandescent lamp containing a certain proportion of halogens." The halogens are iodine, chlorine, bromine, and fluorine. Thus the quartz-iodine-tungsten filament lamp is a member of this class. The lamp is basically an incandescent lamp, producing light and heat from the incandescence of its coiled filament. Unlike the normal inert gas-filled incandescent lamp, the lamp envelope, which is quartz to withstand high temperature, is filled with an iodine vapor that prevents the evaporation of the tungsten filament.

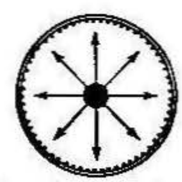
This evaporation is what normally occurs n the incandescent lamp, resulting in the blackening of the bulb, light output deterioration, and eventual burnout. The mechanism of the regenerative halogen cycle is shown in the figure below, along with a graphic comparison of light loss between a normal incandescent and a tungsten-halogen lamp. Although the lamp has approximately the same efficacy as an equivalent normal incandescent, it has the advantages of longer life, low lumen depreciation (98% output at 90% life), and a smaller envelope for a given wattage. Some typical lamp data are given in this table.

Typical Data for Quartz Tungsten-Halogen Lamps, Par, Reflector, and Tubular 120-v Lamps for Spot, Flood, and General Lighting[a]

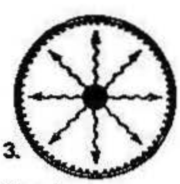
Watts	*Bulb*	*Maximum Overall Length (Inches)*	*Base*	*Rated Life (Hours)*	*Beam Type*	*Approximate Initial Total Lumens*	*Mean Lumens Through Life (Percentage)*
250	PAR-38	$5\frac{5}{16}$	Medium skirted	6000	Spot flood	3220 3220	94 94
500	PAR-56	5	Mogul end prong	4000	Narrow spot Medium flood	8000 8000	94 94
1000	PAR-64	6	Extended mogul end prong	4000	Narrow spot Medium flood	19,400 19,400	94 94
1000	R-60	$10\frac{1}{8}$	Mogul	3000	Flood	18,300	95
250	T-4	3	DC bay	2000	—	4850	95
300	T-4	$3\frac{1}{8}$	RSC	2000	—	5650	95
400	T-4	$3\frac{5}{8}$	Mini-can	2000	—	7970	95
500	T-4	6	Med.-PF	2000	—	10,450	95
750	T-6	6	Med.-PF	2000	—	15,750	95
1000	T-6	$5\frac{5}{8}$	RSC	4000	—	19,800	95

1.


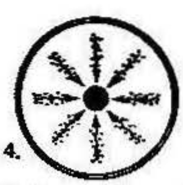
Filament operates at high temperature in close confinement.

2.


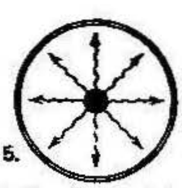
Tungsten particles burn off filament, deposit on bulb wall.

3.


Bulb heats over 500°F—iodine vapor circulates starting bulb-cleaning cycle.

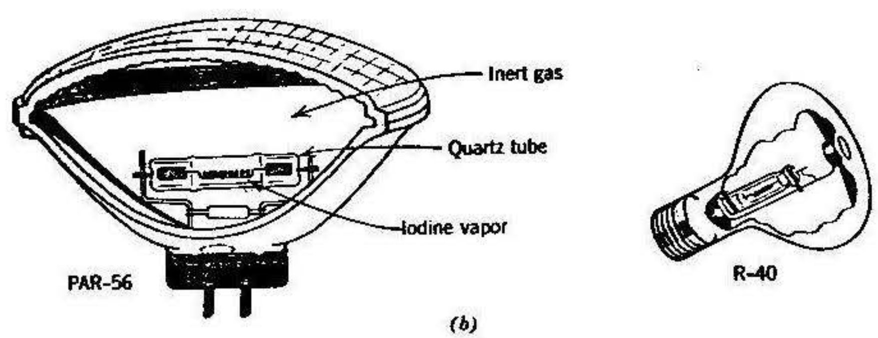
4.


Iodine combines with free tungsten particles, cools and recirculates to filament.

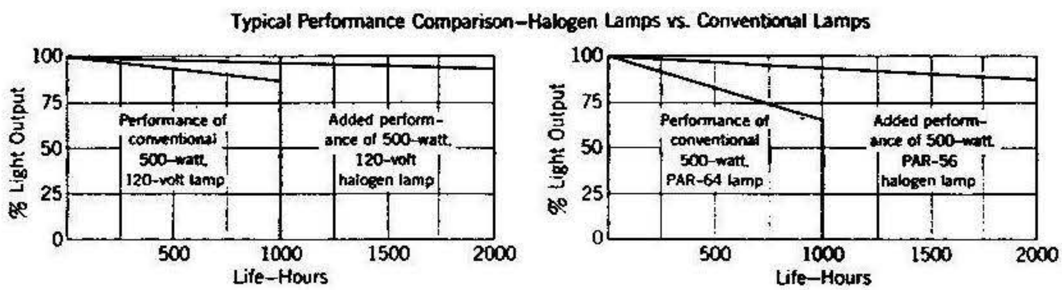
5.


Iodine is reheated by filament, releases tungsten particles and recirculates in a renewed cleaning cycle.

(a)



(b)



(c)

FLUORESCENT LAMPS

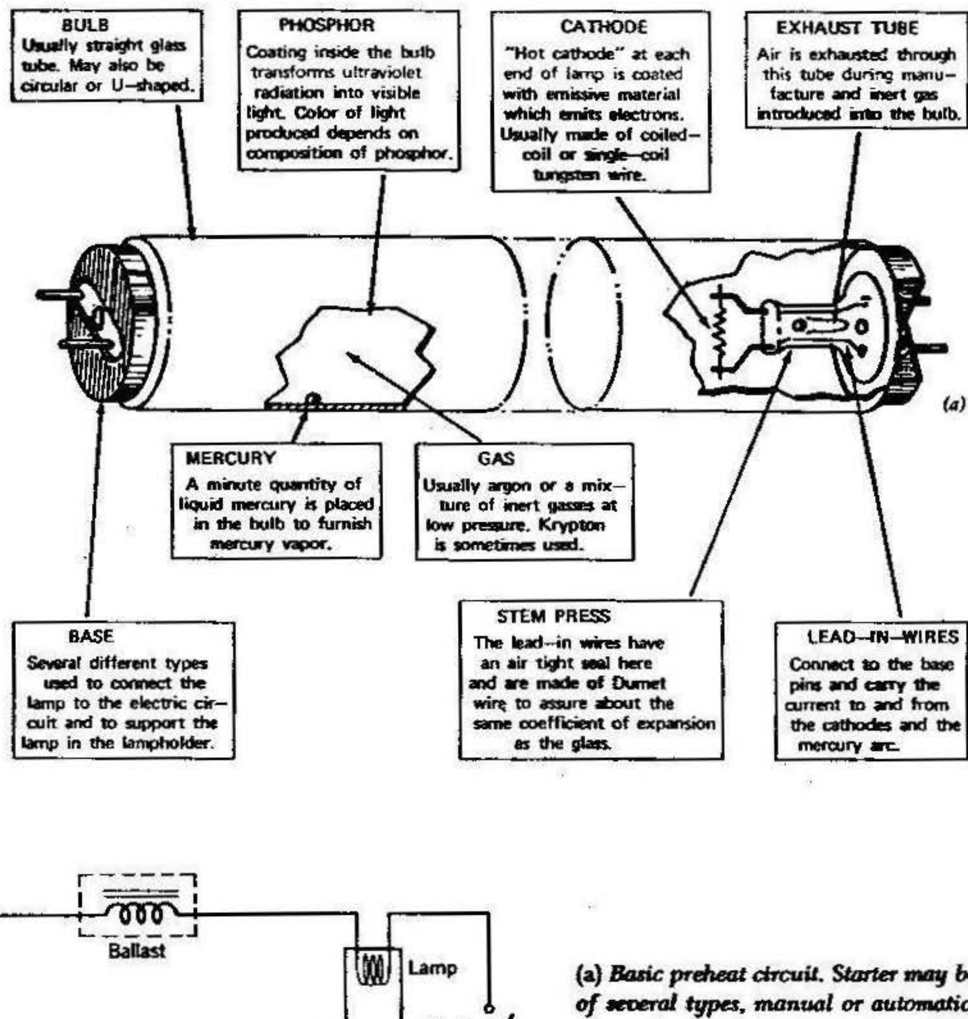
The Fluorescent Lamp-Construction

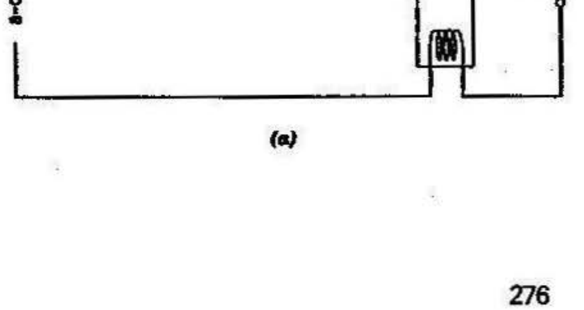
The second major category of light sources is that of electric discharge lamps, of which the fluorescent lamp is the best known and most widely used type. It has become so popular since its major introduction in 1937 that it has almost completely supplanted the incandescent lamp in all fields, except specialty lighting and residential use. The typical fluorescent lamp comprises a cylindrical glass tube sealed at both ends and containing a mixture of an inert gas, generally argon, and low-pressure mercury vapor. Built into each end is a cathode that supplies the electrons to start and maintain the mercury arc, or gaseous discharge. The short-wave ultraviolet light, which is produced by the phosphors with which the inside of the

tube is coated and is reradiated in the visible light range. The fluorescent lamp is so called because its phosphors fluoresce, or radiate light, when exposed to ultraviolet light. The particular mixture of phospors used governs the spectral quality of the light output.

(a) PREHEAT LAMPS

The original fluorescent lamp was of a preheat design. Construction of a typical hot cathode lamp (preheat and rapid start is shown in the figure below; the basic preheat circuit is shown in the next figure).

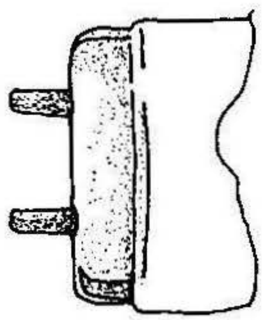




(a) Basic preheat circuit. Starter may be any of several types, manual or automatic. The circuit does not show compensators or other detailed elements for the sake of clarity. Most preheat lamps are T-12 and operate at 425 ma.

The circuit utilizes a separate starter, which is a small cylindrical device that plugs into a preheat fixture. When the lamp circuit is closed, the starter energizes the cathodes; after a 2- to 5- second delay, it initiates a high voltage arc across the lamp, causing it to start. Most starters are automatic, although in desk lamps the preheating is accomplished by depressing the start button for a few seconds and then releasing it. This closes the circuit and allows the heating current to flow; releasing the button causes the arc to strike.

All preheat lamps have bipin bases (see figure below.) They range in wattage from 4 to 90 W and in length from 6 to 90 inches (0.15 to 2.25 M.). A typical ordering abbreviation for a preheat lamp would be F15T12WW. This translates: Fluorescent lamp, 15W, tubular-shaped bulb, 12/8-in. diameter (number represents diameter in one eighths of an inch), warm white color see table below). In large measure preheat lamps have been supplanted by rapid-start and instant-start types.



T-12
MED. BI-PIN
(b)

(b) RAPID-START LAMPS

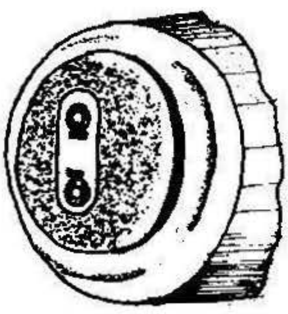
These are similar in construction to the preheat lamps; the basic difference is in the circuitry (see circuit diagram figure below). This circuit eliminates the delay inherent in preheat circuits by keeping the leamp cathodes constantly energized (preheated). When the lamp circuit is energized, the arc is struck immediately. No external starter is required. Because of this similarity of operation, rapid start lamps will operate satisfactorily in a preheat circuit. The reverse is not true, because the preheat requires more current to heat the cathode than the rapid-start ballast provides. (See table below)

Fluorescent Lamp Interchangeability

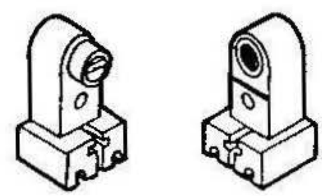
Lamp Type	*Ballast/Circuit Type*		
	Preheat	*Rapid-start*	*Instant-start*
Preheat	OK	Not good, poor starting	Not good, poor starting short life[a]
Instant-start (Slimline)	Won't start, not good[b]	Won't start, Not good[b]	OK
Rapid-start	OK	OK	Not good, poor starting short life[a]
Preheat/ rapid-start	OK	OK	Not good, poor starting short life[a]

By far the most popular lamp is the 40-W T-12 lamp. A standard ordering abbreviation for a lamp would be F40T12WW/RS which indicates fluorescent, 40W, T-12 bulb, warm white čolor, rapid start.

Most rapid-start lamps operate at 425 Ma. If this current is increased, the output of the lamp also increases. Two special types of higher output rapid-start lamps are available. One operates at 800 Ma (milliamperes) and is called simply high output (HO). The second, which operates at 1500 Ma (1.5 amp), is called by different manufacturers — very high output (VHO), super-high output, or simply 1500-ma, rapid start lamp. There is also a 1500-ma special lamp that uses what looks like a dented or grooved glass tube. This lamp, called Power Groove by the standard VHO tube. All high-output lamps use double contact bases and special ballasts (see figures below).



T-12
RECESSED
DOUBLE CONTACT



Recessed double contact
High output lamps
and very high output lamps

(e)

This lamp is used in applications where high output is required from a limited size source such as outdoor sign lighting, street lighting, and merchandise displays. Because of the serious heat problems involved, VHO lamps are frequently operate without enclosing fixtures.

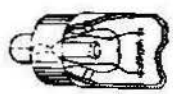
The HO and VHO lamps are slightly less efficient than the standard 425-ma, rapid-start lamp and have considerably shorter life. Typical ordering abbreviations for high-output lamps are similar to the standard rapid-start lamps except that the number indicates length, not wattage. For instance, F72T12/CW/HO is fluorescent, 72-in. lon, T-12 bulb, cool white, high output (1500 ma). Typical characteristics for all rapid-start lamps are given in the table below.

Typical Fluorescent Lamp Data

Lamp Abbreviation	Lamp Data: Lamp (Watts)	Lamp Data: Diameter (Inches)	Lamp Data: Length (Inches)	Lamp Current (milliamperes)	Ballast Watts[b,c]	Total[h] Watts	Lamp Life (Hours)[d]	Initial Output Lumens[e]	Lumens at 40% Life	Initial: Actual Efficacy (lpw)[f]	Initial: Lamp Efficacy (lpw)[g]	Remarks
Preheat lamps[a]												
F15 T8 CW	15	8/8	18	425	8	23	7500	870	750	38	58	Cool white
F20 T12 CW	20	12/8	24	425	10	30	9000	1300	1155	43	65	
Rapid start—preheat lamps[b]												
F30 T12 CW	30	12/8	36	425	7.5	37.5	18000	2300	1955	61	77	
F40 T12 CW	40	12/8	48	425	6	46	20000	3150	2770	68	79	
F40 T12 WW	40	12/8	48	425	6	46	20000	3200	2770	70	80	Warm white
F40 T12 CWX	40	12/8	48	425	6	46	20000	2200	1825	48	55	Cool white deluxe
F40 T12 D	40	12/8	48	425	6	46	20000	2600	2290	57	65	Daylight
F40 T12 CW/S	40	12/8	48	425	6	46	15000	3250	2960	71	81	High lumen maintenance
F40 T12 H	40	12/8	48	425	6	46	20000	2100	1745	46	53	Natural (soft) white
F40 T12/C50	40	12/8	48	425	6	46	20000	2200	1890	48	55	5000 K color
F40 T12/C75	40	12/8	48	425	6	46	20000	2000	1720	44	50	7500 K color
F40 T12/U	40	12/8	—	425	6	46	12000	2900	2525	55	63	"U" shape[i]
Rapid start—high output												
F48 T12 CW/HO	60	12/8	48	800	12.5	72.5	12000	4300	3740	55	72	
F60 T12 CW/HO	75	12/8	60	800	15	90	12000	5400	4700	60	72	
F72 T12 CW/HO	87	12/8	72	800	13	100	12000	6650	5785	67	76	
F96 T12 CW/HO	112	12/8	96	800	14	126	12000	9200	8005	73	82	
Rapid start—very high output												
F48 T12 CW/VHO	116	12/8	48	1500	5	121	9000	6250	4750	52	54	
F72 T12 CW/VHO	168	12/8	72	1500	5	173	9000	9900	7720	57	59	
F96 T12 CW/VHO	215	12/8	96	1500	10	225	9000	14500	11310	64	67	
F48 PG17 CW	116	12/8	48	1500	5	121	12000	7450	5950	62	64	G.E. Power Groove®
F72 PG17 CW	168	12/8	72	1500	5	173	12000	11500	9200	66	68	G.E. Power Groove®
F96 PG17 CW	215	12/8	96	1500	10	225	12000	16000	13000	71	74	G.E. Power Groove®
Instant start (Slimline) lamps												
F42 T6 CW	25	6/8	42	200	13	38	7500	1750	1490	44	70	
F64 T6 CW	38	6/8	64	200	13	51	7500	2800	2350	56	70	
F24 T12 CW	20	12/8	24	425	14	34	7500	1150	990	34	58	
F48 T12 CW	39	12/8	48	425	12	51	9000	3000	2760	54	75	
F72 T12 CW	57	12/8	72	425	13	73	12000	4600	4280	51	65	
F96 T12 CW	75	12/8	96	425	13	88	12000	6300	5800	68	84	
F36 T12	30	12/8	36	425	13	43	7500	2000	1740	47	67	Warm white
Energy-conserving lamps												
F40 CW/RS[j]	35	12/8	48	425	6	41	20000	2850	2510	70	81	Rapid Start, Cool white
F96 CW/HO[j]	95	12/8	96	800	14	109	12000	8500	7395	78	89	RS, High Output
F96 CW[j]	60	12/8	96	425	13	73	12000	5600	5150	76	93	Slimline, Cool white
F96 PG CW[j]	185	—	—	—	13	198	12000	14000	—	71	76	G.E. Power Groove®

(c) INSTANT-START FLUORESCENT LAMPS

Slimline lamps are the best-known variety of instant-start fluorescent lamps. They use a high-voltage transformer to strike the arc without any cathode preheating. These lamps have only a single pin at each end that also acts as a switch to break the ballast circuit when the lamp is removed, thus lessening the shock hazard. (see figures below)

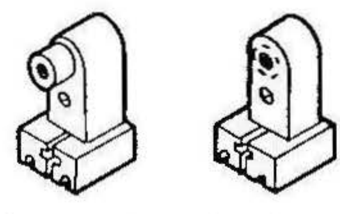


(f)

Base Types

T—12
Single pin

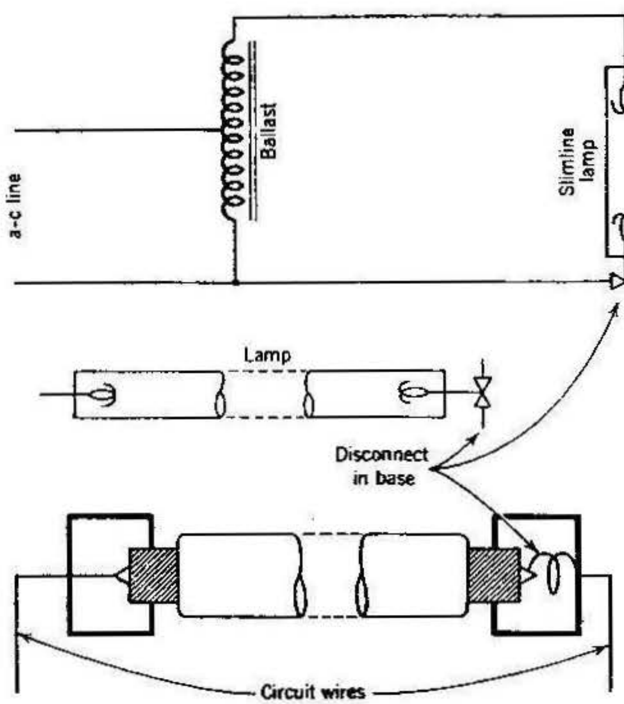
(g)



High voltage end   Low voltage end

Slimline Lamps

(h)



(c)

(c) *Basic instant-start circuit. Voltage from ballast transformer is high enough to strike an arc directly. Note that unlike preheat and rapid-start lamps, these are single pin, since cathodes are not preheated. T-6 and T-8 lamps normally operate at 200 ma, T-12 lamps at 425 ma.*

(Lower portion of figure)
Because of the high voltage involved, the lampholder at one end is a disconnecting device that opens the circuit when the lamp is removed.

The lamps are generally operated in two-lamp circuits at various currents; normal currents are 200 and 425 ma, and normal lengths are 24, 36, 42, 48, 60, 64, 72, 84, and 96 in. (0.60, 0.90, 1.15, 1.20, 1.50, 1.60, 1.80, 2.10, and 2.40 M.) These lamps are actually hot cathode instant-start lamps, which differentiates from the high-voltage cold cathode type. Slimline lamps and ballasts are more expensive than rapid-start and are somewhat less efficient. However, they are manufactured in certain sizes and currents not made in rapid-start (ex: 96 in. 430 ma), and they have the additional advantage of being able to start in much lower ambient temperatures (below 50 °F) than rapid-start circuits. This starting characteristics makes the instant-start circuit particularly applicable to outdoor use. A typical ordering description for such a lamp would be: F42T6CW Slimline, which means: fluorescent, 42-in., length tubular 6/8-in. diameter, cool white, instant start. The T-6 narrow tube indicates a low-current, 200-ma lamp, in lieu of T-12 for the 425-ma lamp. Note also that in instant-start lamps the number following F indicates length, not wattage. This is true of all lamps that operate at other than 425 ma, which is the normal current. Typical characteristics appear in the previous table under pre-heat lamps.

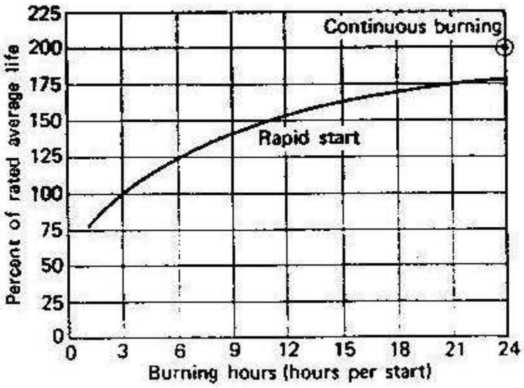
(d) COLD CATHODE TUBES

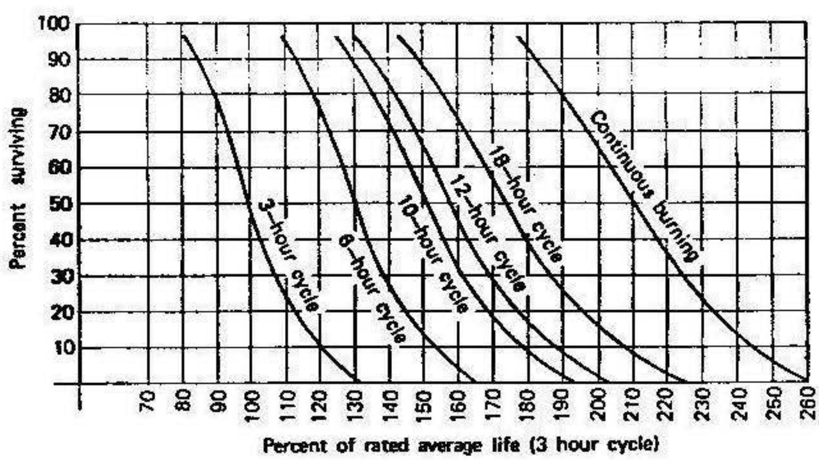
The true cold cathode tubes uses a large, thimble-shaped cathode and a high-voltage transformer that literally tears the electrons out of the large cathode to strike the arc. These lamps have a very long life which, in contradistinction to hot cathode lamps, is virtually unaffected by the number of starts. Cold cathode lamps have a lower overall efficiency than the hot cathode types and are normally used where long continuous runs are required, as in architectural-type lighting rather than in lighting fixtures. Cold cathode lamps are readily dimmed and also operate well at varying ambient temperatures.

The Fluorescent Lamp-Characteristics and Operations

(a) LAMP LIFE

This is dependent on the burning hours per start. The figures listed in the previous table on Typical Fluorescent Lamp data and in the lamp catalogs for lamp life are based on a burning cycle of 3 hr. per start and represents the average life of a group of lamps; That is, half of the lamps of any group will have burned out at this time. Typical lamp mortality curves are shown in figure (a) and the effect of burning hours per start is shown in figure (b)





The significance of this item is connected with energy costs and utilization. From an energy source viewpoint, if an area is not utilized for periods of 15 min. or more, fluorescent lamps should be shut off. This takes into account the resource energy required to replace a tube as a result of shortening its life. From a cost viewpoint, the break-even point depends on these factors:

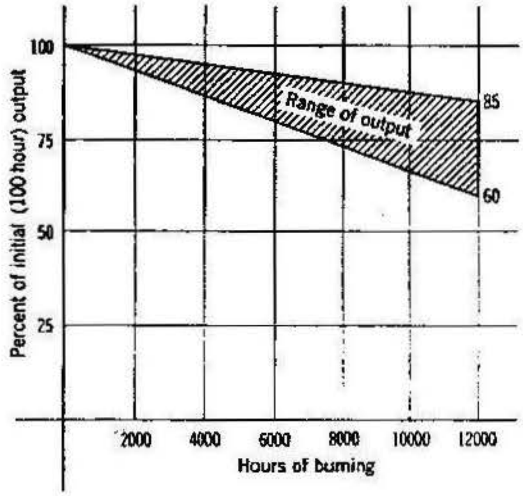
1. Lamp life reduction as a function of burning hours per cycle
2. Cost of energy
3. Cost of lamp and lamp replacement
4. Amount of time lamp remains off when shut off
5. Cost of switching equipment (if any)
6. Life of the building

(b) LUMEN OUTPUT

The lumen output of a fluorescent tube decreases rapidly during the first 100 hr. of burning and thereafter much more slowly. For this reason the tabulated initial lumen

figures represent output after 100 hr of burning. Data are also generally published on the lumen output at 40% of average rated life.

This figure is approximately 85 to 90% of the 100-hr initial value.



(c) EFFICACY

The efficacy of a fluorescent lamp depends on operating current and the phosphors utilized. The figure shown here shows the energy distribution of a typical fluorescent lamp alone, not including ballast losses. Normally warm white lamps are most efficient, followed closely by cool white, white, daylight, and colored lamps. Specially colors such as "natural" white, or lamps designated to produce specific kelvin temperatures, are low in output, with lamp efficacies in the 40 to 50 lpw region. The range of efficacy for standard lamps is 40- to 85 lpw, including ballast losses in the wattage figure. This is important, since discharge lamps are inoperative without ballasts, and neglecting ballast losses yields an artificially high and therefore misleading efficacy.

Generally, standard 425-ma lamps are most efficient, followed by HO 800-ma lamps, then VHO 1500-ma lamps. Specialty lamps such as reflector and low-wattage units are discussed in the following paragraphs. Ballast losses, which constitute 5 – 12% of lamp wattage, depend on ballast type, circuit, manufacturer, and number of lamps connected.

(d) TEMPERATURE

The temperature of the tube, which is also an important factor in light output, is affected by the ambient temperature. Maximum efficiency occurs with the tube operating at a bulb temperature of 100 to 200 °F, with output reduction above and below these values.

(e) VOLTAGE

Voltage either above or below rating adversely affect life, unlike the effect of low voltage on the incandescent lamp. The results of operation at other than rated voltage are shown graphically in this figure. Normal operating voltage range for ballasts is 110 to 125 V on 120-V circuits, 200 to 215 V on 208-V circuits, and 250 to 290 V on 277-V circuits.

(f) DIMMING AND LOW-OUTPUT

Dimming and low-output operation are accomplished by the use of special one-and two-lamp ballasts, with appropriate controls in the case of dimming. Smooth dimming control down to 1% output is possible with solid-state electronic dimming, with the lamp starting at any level. When specifying dimming equipment, care should be exercised to select high-quality SCR controls, so as to avoid causing radio frequency interference (RFI). The cost of dimming equipment is very high and is only justified when smooth changes and unlimited choice of light level are mandatory. Where it is desired simply to be able to reduce the lighting level, as in classrooms, lecture halls, or multipurpose areas, two-and three-level ballasts are available for one or two 40-W, 48-in RS lamps.

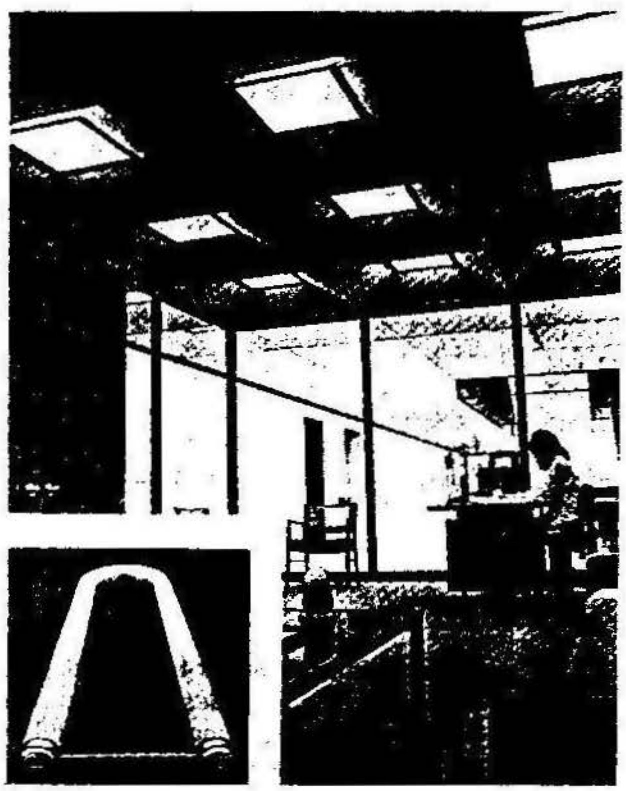
(g) OTHER CHARACTERISTICS

Fluorescent lamps are large and therefore necessitates a relatively expensive fixture both to hold the lamps and control the light — since the tubes emit light throughout their considerable length, accurate beam control is not possible, making fluorescent units best applicable to area lighting. The advantage of fluorescent lamps are long life, low cost, high output and efficacy, availability in an extremely wide range of sizes, colors, and brightnesses, and relative insensitivity to voltage fluctuation (important in brownout areas). Disadvantages are large size, which creates storage, handling, and relamping problems, and the fixture situation previously referred to.

Special Fluorescent Lamps

(a) "U"-SHAPED LAMPS

This were developed to answer the need for a high-efficiency fluorescent source that could be utilized in a square fixture, since the normal fluorescent lamp shape is frequently not architecturally suitable. See figure.



The U lamp is basically a standard 40-W, 48-in. fluorescent tube bent into a U shape and available with 3 5/8 or 6 in. leg spacing; the former can be accomodated three to a 2-ft sq. fixture. and the latter two to a 2 ft. sq. fixture. The lamps operate on standard ballasts and have slightly lower output. than the corresponding straight tube. Insofar as energy as energy is concerned, their use is much more desirable than using 2-ft lamps, as can readily be seen from the following data.

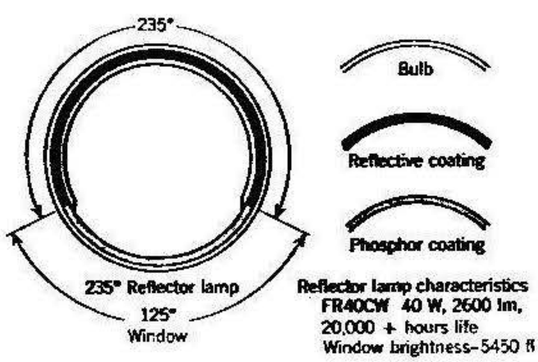
Two foot square fluorescent fixture with four 2-ft cw lamps 110 w 5200 lm

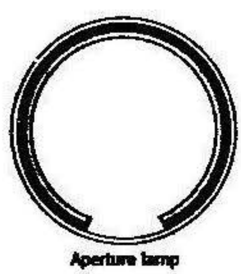
9000-hr life.

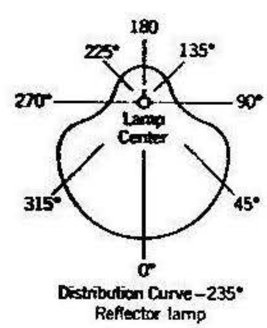
Two U-shaped, cw lamps 100 w 5800 lm
12,000-hr life

(b) **Reflector and Aperture Lamps**

These lamps contain an internal reflector that performs in the same fashion as the more common reflector in the incandescent R and PAR lamp. The reflector lamp is completely phosphor-coated, while the aperture lamp has a clear "window" resulting in very high luminance of this slot.







Both types have lower efficacy than a normal tube and are generally applied where an enclosing fixture is uneconomical or impractical, as in handrails or for sign illumination.

Tests using 235° reflector lamps in normal fluorescent fixtures intended for standard tubes indicate that the fixture coefficient of utilization increases up to 50%, depending on the fixture design. This is because the light normally trapped between the tubes and the fixture is saved, since almost no light is radiated above 62.5° from the vertical (cut-off of the internal reflector). Thus, using reflector lamps for general illumination can result in considerable savings in energy costs.

(c) **Energy-Conserving Lamps**

These lamps are produced by all three major manufacturers and have trademark names.

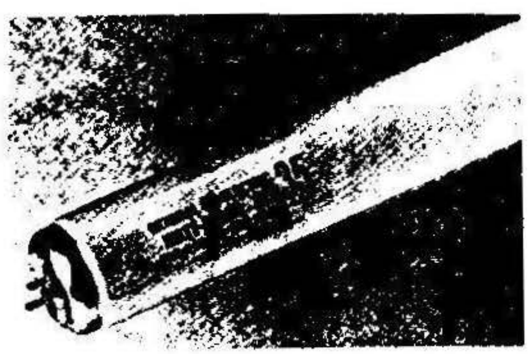
WATT-miser by General Electric
Econo-watt by Westinghouse
Super-saver by Sylvania

These lamps are intended as lower-wattage replacements for standard lamps.

Comparative wattages follow.

Standard Lamps	Energy-Conserving Lamps
48 in., 40 w	34 w
96 in., 112 w Ho	95 w
96 in., 215 w VHo	185 w
96 in., 75 w slimline	66 w

It is important to know that although the efficacy of these energy-saving lamps is higher than their standard counterparts, their output is lower and life is shorter (except for the 40-w unit). This means that the application is most appropriate where direct substitution for standard lamps is possible and the corresponding reduction in lighting levels is acceptable. This is frequently the case in stores, corridors, walkways, and many offices. Low energy lamps are clearly marked by the manufacturer as can be seen in the figure below.



Energy-saving lamps are clearly so marked, as shown. Illustrated is General Electric's 35-w, T12 rapid start unit; intended to replace the standard 40-w lamp. The illustrated lamp has substantially the same output as a standard lamp, thus resulting in no foot candle loss when replacement is made.

NEON LAMPS

Neon vapor lamps consist of exhausted glass tubes filled with neon gas that is ionized and conducts an electric current through the tube. A high voltage is required because of the large voltage drop at the cathode; consequently, a transformer is a necessary part of the equipment. A step up from 115 to 6000 or 10,000 V may be required. Neon light has a pink to dark red color, depending on the gas pressure. The tubes are commonly used in street, window and indoor signs.

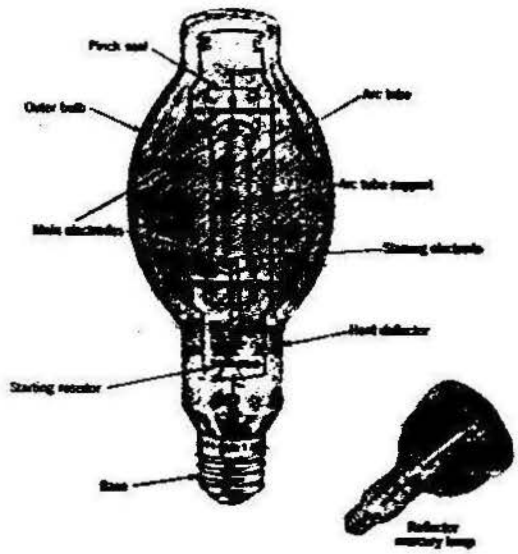
Different colors may be obtained by using mixtures of the two, or by using colored glass tubing.

HIGH-INTENSITY DISCHARGE (HID) LAMPS

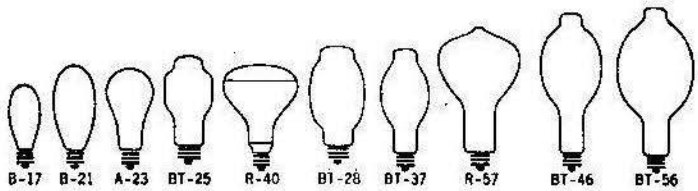
These lamps have inherently high efficacy and, with appropriate color correction, can be utilized in any application, indoor or outdoor, that does not have critical color criteria.

MERCURY LAMPS

These lamps operate by passing an arc through a high-pressure mercury vapor contained in an arc tube made of quartz or glass. See figure.



This action produces light in both the ultraviolet region (as in the low-pressure fluorescent lamp tube) and in the visible region, principally in the blue-green band. This color is characteristic of the clear mercury lamp.



Explanation of color suffix in ordering abbreviation:

/DX Deluxe White	/R Beauty Lite
/N Style-Tone	No suffix—Clear (non-phosphor coated)

Descriptive Symbols

B Black Light	RF Reflector Flood
FF Frosted Face	S Street Lighting
G General Lighting	VW Very Wide Beam
W Wide Beam	

(a) **Lamp Designations**

The American National Standard Institute (ANSI) adopted a simplified code some time ago that is now used by all manufacturers. This code has five parts and is best illustrated by example. Lamp designation

H38 mp 100 DX indicates:

H — mercury lamp
38 — Ballast number
MP — indicates lamp physical characteristics
100 — lamp wattage
DX — Identifies phosphor, glass coating, or coloring. Optional with each manufacturer. Lack of a letter indicates a clear lamp.

(b) **Lamp Life**

Lamp life is extremely long, averaging 24,000 hours based on 10 burning hours per start. Mercury lamps are not suitable for applications that are subject to constant switching: Therefore, a long period of burning per start was selected. Life is affected by ambient temperature, line voltage and ballast design. Mercury lamps are not as sensitive to short burning cycles as fluorescents but, because of accelerated lumen depreciation near the end of life, they are normally replaced before burnout.

(c) **Color Correction and Efficacy**

These are added because the blue-green light distorts almost all colors. The outer bulb is coated with phosphors that are excited by the UV light and are reradiated generally in the red band, which is entirely absent in the basic lamp color. Depending on the arc tube design and the phosphors used, the color of the emitted light can be corrected to make it acceptable for general indoor use. Lamps are available in clear, white, color-corrected, and white-deluxe, in ascending order of color improvement.

The deluxe lamp also uses a strain on the envelope to filter out some of the blue-green, which obviously reduces lamp output.

(d) **Ballast**

Ballasts are required, as with all arc discharge lamps, to start the lamp and thereafter to control the arc. The basic ballast is simply a reactor that controls the arc after the discharge has been initiated. Three to six minutes are required for the lamp to reach full output, since heat must be generated by electron flow to vaporize the mercury in the arc tube before the arc will strike. Once extinguished, the lamp must cool and the pressure must be reduced before restrike is possible. This restart delay amounts to 3 to 8 min., depending on the ballast type, and is an important consideration in design.

(e) **Dimming**

Dimming of mercury lamps is possible and entirely practicable with the use of dimming ballast and solid-state dimming control. These are available for 400-. 700-, and 1000- W units and, unlike the case of fluorescents, dimming is a desirable and economical control means. Mercury lamps have so large an output that shutting off a unit creates an imbalance in the lighting — coverage — a problem readily solved by dimming.

A little used but very effective and economical output reduction technique is simply to change the circuit capacitance by an amount, depending on lamp size and ballast type. By doing this, the lamp wattage and output can be reduced by approximately 50% with no deleterious effect on lamp or ballast. This technique is by far the chapest method of accomplishing an overall, even reduction in output.

(f) **Application**

Mercury-vapor lamps are applicable to indoor and outdoor use with proper attention to color and fixture brightness. Indoor application is generally limited to mounting 10 AFF or higher to avoid glare problems and to permit adequate area coverage. Use in industrial spaces and stores is common.

Special Mercury Lamps

In an attempt to satisfy the desire for a small lamp to take the place of incandescents in interior fixtures, manufacturers have made available mercury lamps in 40-, 50-, 75-, 100-, and 175-W sizes, in deluxe white and other color-corrected designs. (see figures above). For the smaller sizes, screw-in-ballasts are available, so that replacing an incandescent is simply a matter of screwing in a ballast and a small mercury lamp. In the 175-W size the ballast must be separately mounted. Available also are self-ballasted lamps (require no separate ballast), which can be used self-ballasted lamps (require no separate ballast), which can be used where ballast mounting is inconvenient, expensive, or undesirable for other reasons. In both cases, there is no doubt that the extremely long life, good color and reliability of these incandescent substitutes make their use attractive in locations where relamping is difficult and expensive.

Metal Halide Lamps

This is basically a mercury lamp that has been altered by the addition to the arc-tube of halides of metals such as thallium, indium, or sodium. The addition of these salts causes light to be radiated at frequencies other than the basic mercury colors and increases efficacy, but reduces the life and reduces lumen maintenance to 60% at two-thirds life. The color produced is much warmer than that of the mercury light. Clear lamps are recommended for exterior use and phosphor-coated units for all indoor application including food displays.

A brief comparison of these two lamps shows:

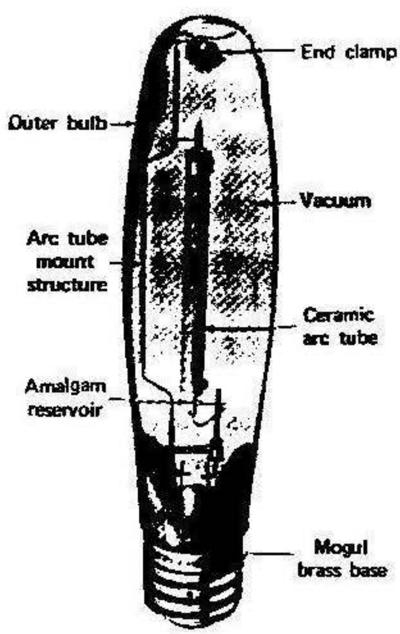
	Mercury	Metal-Halide
Life	16,000 to 24,000 hr.	7,500 to 15,000 hr.
Color	poor to fair	good to excellent
Lamp efficacy	50 to 60 lpw	80 to 100 lpw

Since the color of the metal-halide lamp depends on the amount of ionized halide salt in the arc, lamp performance is extremely sensitive to voltage, temperature, and burning position. Mortality and lumen maintenance curves are similar to those for mercury lamps except for lower values. Strike time is shorter than that of the mercury lamp, being two to three minutes, but restrike time is up to 10 min., making it necessary to supply an instant start source in indoor areas lighted with these lamps.

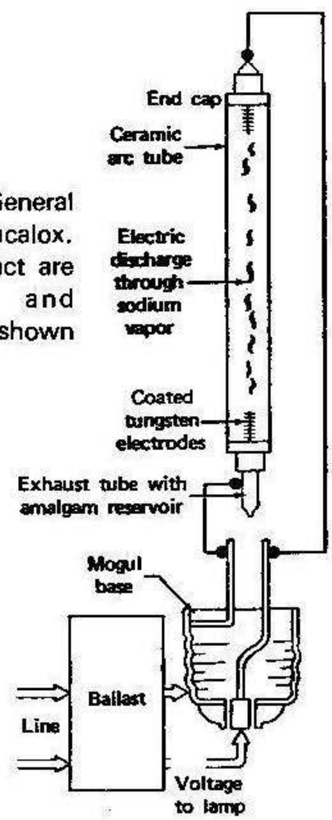
Common trade names for these lamps are metal-arc (Sylvania), multivapor (G.E.), and metal halide (Westinghouse).

HIGH-PRESSURE SODIUM (HPS) LAMPS

This is marketed by its developer, General Electric, under the trade name Lucalox. Other trade names for this product are Westinghouse's Ceramalux and Sylvania's Details of the lamp are shown in this figure.



(a)



(b)

Construction is quite different from that of mercury and metal-halide lamps and, although it operates as an arc discharge unit, its excellent characteristics stem from the spectral absorption phenomenon of the contained sodium under high pressure. The resultant light is a yellow-tinted color, similar to that of warm white fluorescent lamps. Typical characteristics are:

Lamp efficacy	25 to 140 lpw.
Efficacy including ballast losses	55 to 125 lpw
Life	16,000 to 24,000 hrs.
Lumen maintenance	80 to 90%
Warm-up time	3 to 4 min.
Restrike time	½ to 1½ min.

Unlike the metal-halide lamp, the HPS unit is not voltage sensitive and is color constant. As with all discharge lamps, a ballast is required to supply the high voltage to strike the arc, and to control the arc once struck. On the average HPS lamps will supply double the efficacy of mercury lamps. These direct mercury replacements are marketed under the trade names of E-Z lux and unalux by G.E. and Sylvania, respectively. HPS lamps are available in clear and coated designs. The clear is effectively a point source and, because of its extreme brightness, must be enclosed in a fixture. The coated is intended to substitute photometrically for coated mercury lamps and to constitute a lesser glare source, since lamp surface brightness is correspondingly reduced.

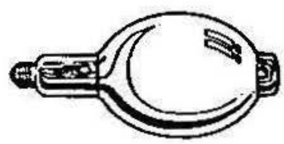
Low Pressure Sodium Lamps

This lamp, also referred to as SOX, produces light of sodium's characteristic monochromatic deep yellow color, making it inapplicable for general lighting. Because of its very high efficacy of over 150 lumens per watt including ballast loss, it can be applied wherever color is not an important criteria. Thus SOX is widely used for street, road, and area lighting, as well as for emergency or after-hours indoor lighting. Another desirable aspect of SOX lamps is their 100% lumen maintenance. This, coupled with the discharge lamp's typically long life (18,000 HRS), make SOX lamps the most economical source available today in terms of cost per million lumens produced.

Example of SYLVANIA HIGH PRESSURE SODIUM LAMPS

Watts	Bulb	Hours/Life	Lumens
70	BT-25	20,000	5,220
100	BT-25	20,000	8,850
150	BT-25	24,000	14,400
150	BT-28	24,000	14,4000
250	E-18	24,000	24,750
400	E-18	24,000	45,000
1000	E-25	24,000	126,000

Watts	Bulb	Hours/Life	Lumens
70	BT-25	20,000	4,860
100	BT-25	20,000	7,920
150	BT-25	24,000	13,500
400	BT-37	24,000	42,750



Watts	Bulb	Hours/Life	Lumens
150	BT-28	12,000	11,700
360	BT-37	16,000	34,000

Watts	Bulb	Hour/Life	Lumens
150	BT-28	1,200	10,800
360	BT-37	1,600	32,400

14

LIGHTING DESIGN

LIGHTING DESIGN

GOALS OF A LIGHTING DESIGN

The goal of lighting is to create an efficient and pleasing interior. These two requirements, that is, the utilitarian and aesthetic, are not antithetical as is demonstrated by every good lighting design. Light can and should be used as an adjunct architectural material.

a. Lighting levels should be adequate for efficient seeing of the particular task involved. Variations within acceptable brightness ratios in a given field of view are desirable to avoid monotony and to create perspective effects.

b. Lighting equipment should be unobtrusive, but not necessarily invisible. Fixtures can be chosen and arranged in various ways to complement the architecture or to create dominant or minor architectural features or patterns. Fixtures may also be decorative and thus enhance the interior design.

c. Lighting must have the proper quality. Accent lighting directional lighting and other highlighting techniques increase the utilitarian as well as architectural quality of a space.

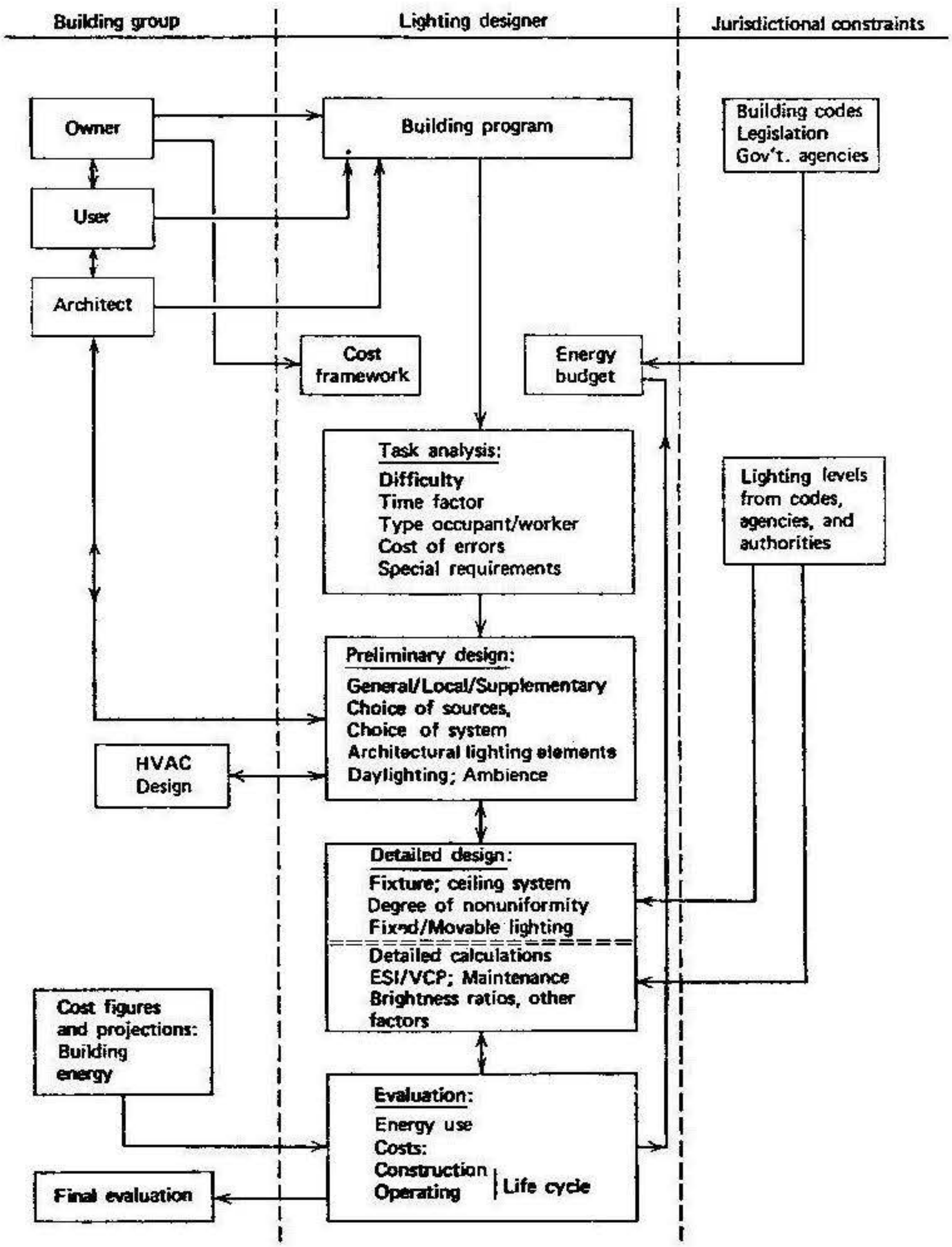
d. The entire lighting design must be accomplished efficiently in terms of capital and energy resources; the former determined principally by life-cycle costs and the latter by operating energy costs and resource-energy usage. Both the capital and energy limitations are, to a large extent, outside the control of the designer, who works within constraints in these areas.

Lighting Design Procedure

(a) Project Constraints

Refer to the flowchart figure. This flowchart represents the design procedure and its interactions, should be referred to throughout the necessarily lengthy discussion that follows, in order to maintain perspective. It is important that the reader be aware of job constraints and of the interactions between the lighting designer and the remainder of the design group. This is deliberately emphasized to demonstrate the inter-disciplinary nature of lighting design in general and its particular connection with HVAC and daylighting (fenestration).

Lighting Design Procedure



1. Owner-Designer — User group.

The owner establishes the cost framework, both initial and operating. As part of both of these may be a rent structure, which in turn determines and is determined by the space usage. If the owner is also the occupant the cost factors change somewhat but remain in force. The architect determines the amount and quality of daylighting and the architectural nature of the space to be lighted. Much of these data are detailed in the building program.

2. The Jurisdictional Authorities
These may include:

FEA — Federal Energy Administration
IES — Illuminating Engineering Society
ERDA — Energy Research And Development Administration.
ASHRAE — American Society of Heating, Refrigeration, and Air-Conditioning Engineers

The principal area of involvement is that of energy budgets and lighting levels, both of which affect every aspect of lighting design including source type, fixture selection, lighting system, fixture placement, and even maintenance schedules. For this reason the first step in the lighting design procedure is to establish the *project lighting cost framework and the project energy budget.*

(b) **Task Analysis**

As shown in the chart, this step essentially determines the needs of the task. Factors to be considered in addition to the nature of the task are its repetitiveness, variability, who is performing it (ex: condition of the occupant's eyes), task duration, cost of errors, and special requirements.

(c) **Design Stage**

This is the active consideration stage during which detailed suggestions will be raised, considered, modified, accepted, or rejected. This is also the most interactive stage as is clearly seen in the chart. At its completion, a detailed, workable design is in hand. The critical interactions here are with the architect in daylighting and with the HVAC group in power loads. The former may result in relocating a space within the building; the latter in making a change in a lighting system or HVAC system. In brief, this stage consist of the following steps:

1. Select the lighting system
Select types of light source, distribution characteristic of fixtures or area source, consider effects of daylighting, economics, and electric loads.

2. Calculate the lighting requirements. Use the applicable calculation method and establish the fixture pattern, considering the architectural effects.

3. Design the supplemental lighting

4. Review the resultant design. Check the design for quality, quantity, aesthetic effect, and originality.

(d) **Evaluation Stage**

With the design on paper, it can now be analyzed for conformance to the principal constraints of cost and energy. If the design stage has been carefully accomplished, with due attention to these factors, the result of the final evaluation should be gratifying. The results of this stage are fed to the architectural group to use in the final overall project evaluation.

Preliminary Design

Energy Considerations

In commercials buildings lighting consumes about 20 to 30% of the buildings electric energy; more in residences and less in industrial facilities. By judicious design a reduction of 40 to 50% in lighting energy is attainable. In point of the fact that every watt per square foot reduction in lighting energy results in 1.25 w / sq. ft. savings in air-conditioned buildings. It has been demonstrated by actual designs that offices and schools can be well lighted with 2.5 w/sq. ft. in lieu of the 4 to 5 w/sq. ft. in common use.

Design Guidelines

1. **Design lighting for expected activity**

This point states that it is wasteful, of energy, to light any surface at a higher level than it requires. Since most spaces contain varied seeing tasks, nonuniform lighting is recommended. In order to accomplish this for areas where exact furniture layout is not available, it may be necessary to furnish readily movable fixtures. A trade-off is involved here between the additional first cost of movable fixtures and the lowered operating cost.

Providing overall high-level illumination with provision for switching to reduce levels is not advisable because of increased first cost and the psychological impetus to operate at maximum levels. Also, use of movable fixtures makes heat removal via ducted air-troffers impractical. A compromise solution here is fixed fixtures for general low level lighting and movable ones for supplementary task lighting. Other factors and techniques to be borne in mind are:

a. Grouping of tasks with similar lighting requirements will generally increase efficiency.

b. Place most severe seeing tasks at best daylight locations.

c. Fixed-position tasks involve nonuniform lighting and vice versa.

d. Heat removal fixtures (air-troffers) increase efficiency of the units 10 to 20% but makes the fixtures immobile trade-off decision involved.

e. Advantages of nonuniform lighting increase as the space between work stations increases.

2. **Design with More Effective Luminaires and Fenestration.**

By effective is meant providing useful light with high ESI component and minimum direct glare. In selecting fixture diffusers a trade-off is often encountered between these two usually mutually incompatible factors. In cases where much of the viewer's time is spent in a head-up position, as in schools, or where the viewer can compensate for veiling reflections, the decision should lean toward high VCP.

Where work position and viewer's are fixed, most of the viewer's time is spent head-down, viewer's room position reduces direct glare, or illumination levels are well below the 100 fc level for which VCP is calculated, the decision should lean low-reflected glare. Fenestration too must be considered as a light in all respects, with particular attention to the deleterious effects of excessive window brightness and the beneficial effects, that is, the excellent quality of daylighting.

3. **Use Efficient Light Sources**

Trade-offs involved here are:

a. Between first cost and life-cycle costs.

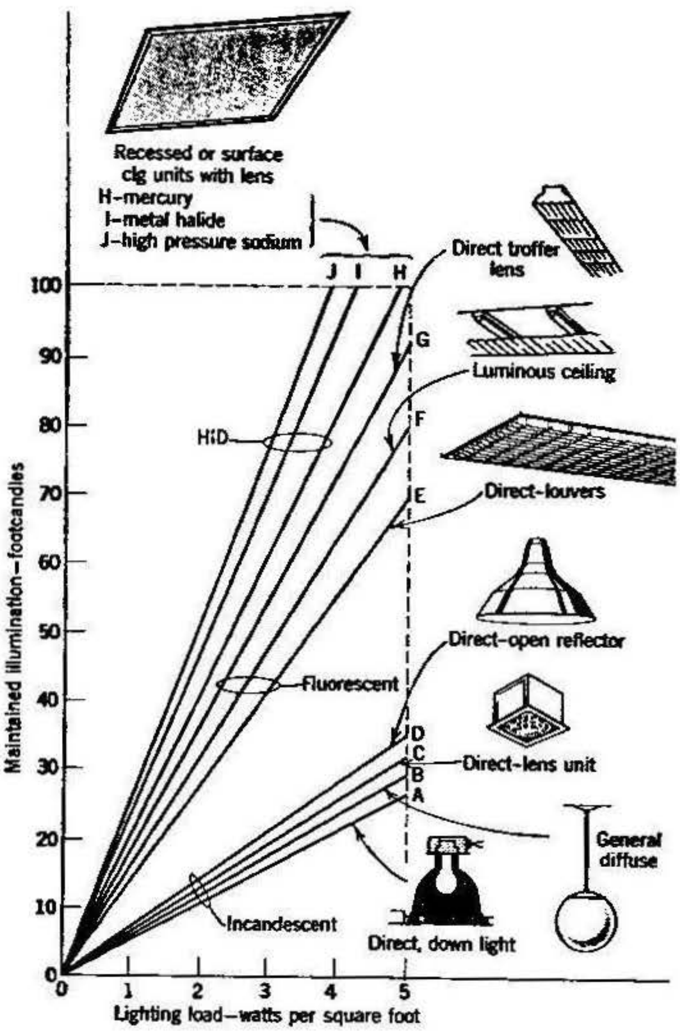
b. Between desired illuminant color and efficiency. For most indoor uses, OFF-white color, as from HPS lamps should be considered.

c. Between light control and efficiency. Fluorescent sources, which are highly efficient, do not lend themselves to good beam control and are principally useful for area coverage.

d. Between architectural requirements and efficiency. Fluorescent sources are efficient and have good color but require a large fixture, which tends to dominate the space. A possible compromise is the U-shaped lamp in a modular ceiling.

The following figure will assist the designer in determining roughly what the various sources represent in terms of watts per square foot load. Thus, with a target of 2 to 2.5 W / sq. ft. for office-building lighting, the use of incandescent downlights is obviously severely restricted. Daylight must be considered as a regular light source subject to weather variations and time of building use. Obviously a three-shift industrial plant cannot use daylight on all shifts, but it can for at least one shift, and design should reflect this fact. Spill light and borrowed light are often neglected sources. Glass in upper wall sections can provide sufficient corridor lighting from borrowed office lighting. Sources with high lumen maintenance such as tungsten halogen and high-pressure sodium should be given preference.

Another aspect of light source efficiency is the ability to reduce levels easily. Use multilevel ballasts and switching to give flexible lighting control. Unused light is wasted energy.



Estimating chart for lighting load and related illumination levels for different lighting sources. The chart was calculated for a fairly large room—approximately classoom size. Although all the figures are necessarily approximate because of the variables involved, the chart gives figures close enough for a first approximation. Notice the increase in output as the sources change from incandescent to fluorescent to HID.

4. **Use More Efficient Luminaires**

This point is connected to the one above in that only by using an efficient source in an efficient enclosure can best results be obtained. By efficient enclosure we mean a fixture with high coefficient of utilization CU and high light loss factor LLF since useful lumens are defined as

$$\text{useful lumens} = \text{generated lumens} \times \text{CU} \times \text{LLF}$$

(see the proceeding sections on luminaire diffusing elements and sections on light loss factor)

Care must be exercised here since simple lampholders have high CU and LLF but of course create direct glare problems. Therefore here also a trade-off is involved between high CU and LLF and high VCP.

Other factors, being equal, select luminaires with a high-maintenance category. Enclosed nongasketed fixtures collect dirt and yield a lower overall LLF. Also the quality of the luminaire finish will have considerable bearing on its performance after 8 to 10 years.

5. **Use Thermal—Controlled Luminaires**

In other words, do not waste the heat generated by lighting and, conversely, avoid placing additional load on the air-conditioning system with lighting heat. With lower lighting levels this point has considerably less significance than it did when 6 to 10 w / sq. ft. lighting loads were common. Disposition of this point depends, to a large extent, on the type of HVAC system, the lighting heat load, and the type of fixtures employed. Detailed analysis of this point involves HVAC considerations and the overall impact of lighting energy on the building.

6. **Use Lighter Finishes on Ceilings, Walls, Floors, and Furnishings.**

A brief summary of recommendation ranges would be:

ceilings - 80 to 92%
walls - 40 to 60%
furniture office machines and equipment - 25 to 45%
floors - 20 to 40%

7. **Use Efficient Incandescent Lamps**

See sections on these item in Chapter XIII.

8. **Turn Off Lights When Not Needed**

The trade-off involved here is between cost of control equipment and energy savings. Here too, as in item 3 above, switching includes reduction of levels by use of multilevel ballasts, dimming, and partial switching. Coordinate this item with item 10 below so that daylight and artificial light complement each other.

9. **Control Window Brightness**

Excessive brightness causes severe and even disabling glare, A corollary of excessive brightness is excessive heat gain. Both are manageable with common control devices, manual and automatic.

10. **Utilize Daylighting as Practicable**

Self-explanatory. See sections on daylighting in chapter XIII.

11. **Keep Lighting Equipment Clean and In Good Working Order.**

Lighting equipment must be selected with life-cycle costs in mind, a large position of which are maintenance and relamping costs. Fixtures in relatively inaccessible locations such as high ceilings must be designed for low maintenance, and maintenance should be on a fixed schedule. Trade-off here is between higher cost of low-maintenance units and high maintenance costs. A corollary is the use of high-lumen-maintenance sources.

12. **Post Instructions Covering Operation and Maintenance**

By operation, we mean fixed scheduling based on known work shift. This can be accomplished automatically with time switches or manually if the scheduling can be enforced. Time switches should have override to permit accomodation to unusual situations. Lighting maintenance is defined here as fixed scheduling of maintenance and relamping. A 20% increase in maintained light is possible if lamps are replaced at the end of their useful life, when output is down to 70% of initial maintained lumens, and fixtures are cleaned and maintained on a fixed schedule.

Preliminary Design

Referring to the figure of the chart earlier, the preliminary design phase is the time during which ideas crystallize, but in terms of areas, patterns, as well as light and shadow; not yet in terms of hardware. At this stage the quality of the system is decided upon, that is, the brightness ratios, diffuseness, Chromaticity, and proportion of vertical to horizontal lighting are determined. The latter establishes in large measure the room "mood" or lighting ambience. In the sections that follow on lighting systems (direct, indirect, etc.) the quality of each will be cosidered and applications suggested. In the overall view, however, the ultimate quality of the lighting system, its visual pleasantness, center of visual attention, highlights and shadows, as well as texture and forms, will be a deft and perhaps artistic combination of the above considerations, and will establish, as the term implies, the quality of the lighting design. A few observations are mentioned below.

Planes other than "working plane" must always be considered. The ratio of vertical to horizontal illumination of the chosen system will determine wall brightnesses, while the floor finish will have a pronounced effect on the ceiling illumination for direct lighting systems.

The chromaticity of the room lighting depends primarily on the source but secondarily on the luminaire and surface finishes. A "white" source can be tinted slightly by the use of a colored reflector in the luminaire. Of course, the effect on luminaire output of such a change must be considered. In the case of semi-indirect and indirect lighting this same effect can be accomplished by the use of colored ceiling and upper wall surfaces, which serve as secondary reflectors and become the actual luminous source for the room.

Comparative Characteristics of Light Sources

	Incandescent		*Fluorescent*		*High-Intensity Discharge (HID)*				
					Mercury				
Characteristic	*Filament*	*Tungsten Halogen*	*Standard*	*High-Output*	*Clear*	*Phos.*	*Self-Ball.*	*Metal Halide*	*High-Pressure Sodium*
Wattages	10–1500	100–1500	15–100	60–200	40–1500	—	150–750	175–1500	70–1000
Efficacy—lamp	15–25	15–25	50–80	55–85	30–65	—	—	80–105	85–140 lpw
Lamp and ballast	—	—	40–70	45–75	25–55	—	15–25	65–85	55–125 lpw
Life-hours	750–1000	2000–6000	12000–20000		16000–24000 hr			—	—
Lumen maintenance @ 50% life	80–90%	95%	85–90%		70–80%		—	75–85%	80–90%
Color acceptability	Excellent		VG	VG	Poor	Fair to good		VG	Fair to good
Start time	Instant	Instant	Instant	Instant	3–6 minutes		—	2–3 min	3–4 min
Restrike time	—	—	Instant	Instant	3–8 minutes		—	5–10 min	$\frac{1}{2}$–$1\frac{1}{2}$ min
Light control	VG	VG	Poor	Poor	Good	Fair	Good	Good	Good
Glare control	VG	VG	VG	Fair to Good	Fair	Good	Good	Fair	Fair
Fixture cost	Low	Low	Low to moderate		Moderate to high			High	Highest
Cost to produce 10^6 lm	See Figure 19.46.								

A Guide for Lamp Selection Based on General Color Rendering Properties

Type of Lamp	Efficacy (lpw)	Lamp Appearance Effect on Neutral Surfaces	Effect on "Atmosphere"	Colors Strengthened	Colors Grayed	Effect on Complexions	Remarks
			Fluorescent Lamps				
Cool[a] white CW	High	White	Neutral to moderately cool	Orange, yellow, blue	Red	Pale pink	Blends with natural daylight—good color acceptance
Deluxe[a] cool white CWX	Medium	White	Neutral to moderately cool	All nearly equal	None appreciably	Most natural	Best overall color rendition; simulates natural daylight
Warm[b] white WW	High	Yellowish white	Warm	Orange, yellow	Red, green, blue	Sallow	Blends with incandescent light—poor color acceptance
Deluxe[b] warm white WWX	Medium	Yellowish white	Warm	Red, orange, yellow, green	Blue	Ruddy	Good color rendition; simulates incandescent light
Daylight	Medium-high	Bluish white	Very cool	Green, blue	Red, orange	Grayed	Usually replaceable with CW
White	High	Pale yellowish white	Moderately warm	Orange, yellow	Red, green, blue	Pale	Usually replaceable with CW or WW
Soft white/ natural	Medium	Purplish white	Warm pinkish	Red, orange	Green, blue	Ruddy pink	Tinted source usually replaceable with CWX or WWX
			Incandescent Lamps, Tungsten Halogen				
Incandescent filament	Low	Yellowish white	Warm	Red, orange, yellow	Blue	Ruddiest	Good color rendering
			High-Intensity Discharge Lamps				
Clear mercury	Medium	Greenish blue-white	Very cool, greenish	Yellow, blue, green	Red, orange	Greenish	Very poor color rendering
White mercury	Medium	Greenish white	Moderately cool, greenish	Yellow, green, blue	Red, orange	Very pale	Moderate color rendering
Deluxe white[a] mercury	Medium	Purplish white	Warm, purplish	Red, blue, yellow	Green	Ruddy	Color acceptance similar to CW fluorescent
Metal halide[a]	High	Greenish white	Moderately cool, greenish	Yellow, green, blue	Red	Grayed	Color acceptance similar to CW fluorescent
High-pressure sodium[b]	High	Yellowish	Warm, yellowish	Yellow green, orange	Red, blue	Yellowish	Color acceptance approaches that of WW fluorescent

Illumination Methods

Three Methods of Illumination

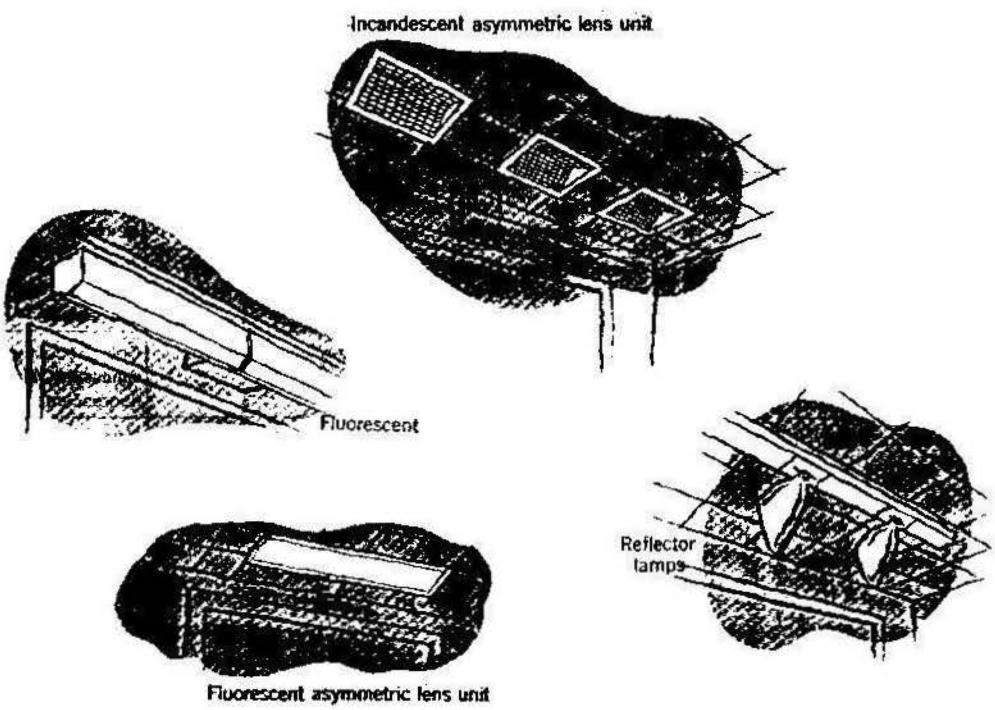
1. General
2. Local and Supplementary
3. Combined general and local

(a) General Lighting

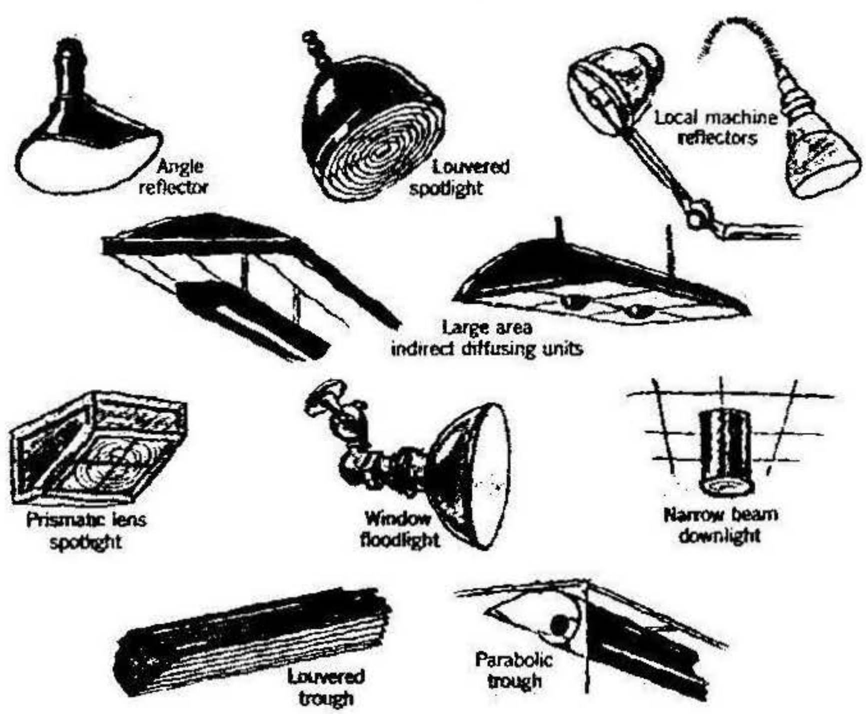
This is a system designed to give uniform and generally, though not necessarily, diffuse lighting throughout the area under consideration. The method of accomplishing this result varies from the use of luminous ceiling to properly spaced and chosen downlights, but the resultant lighting on the horizontal working plane must be same, that is, reasonably uniform. It may be, but is not necessarily, task lighting.

(b) Local and Supplementary Lighting

These are two terms that are used interchangeably but have slightly different meanings. By definition, local lighting provides a small, high-level area of lighting without contributing to the general lighting, supplementary lighting also provides a restricted area of high intensity, but supplements the general lighting. In actual practice, it is difficult to differentiate between the two. A desk lamp, a high-intensity downlight on a merchandising display, and a track light illuminating wall displays, all seem to answer both definitions, and in practice are referred to as local, supplementary, or local-supplementary lights. See figures below.

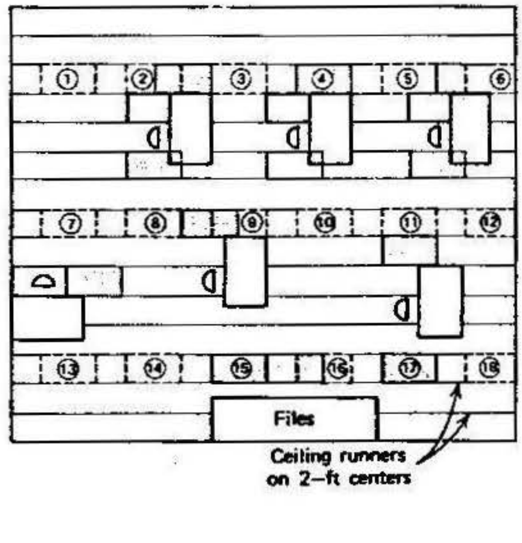


Chalkboard Lighting Units



(c) **Combined General and Local Lighting**

This illumination method is used in areas where the general visual task is low, but local high-intensity lighting is required. An excellent example is the department store where circulation requires low-level lighting while merchandising areas and showcases require up to 500 fc. The indicated solution to this problem is a general lighting system that will provide 30 fc of uniform, diffuse lighting of the proper color and supplementary local lighting in restricted areas. The quality of the local lighting supplied depends on the particular item being displayed. A nonuniform lighting layout that is arranged to localize lighting but does not have a uniform overall pattern is difficult to classify. We would think of it as a combination of general lighting in some areas and local in others, that is, a combined system. See figure below.

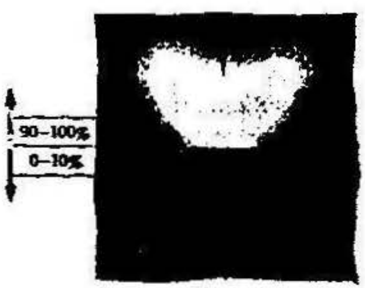


These three methods of illumination can be accomplished in many ways by the use of luminaires and luminous sources of different types, since the illumination method is a function of both fixture placement and arrangement as well as the inherent fixture lighting distribution. The term used to describe the effect of the combination of a particular fixture type applied in a particular way is the lighting system. Thus a reflector-type fixture when aimed down gives direct light. The same fixture beamed up at the ceiling gives indirect light.

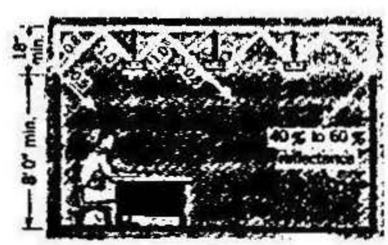
Types of Lighting System

1. Indirect Lighting

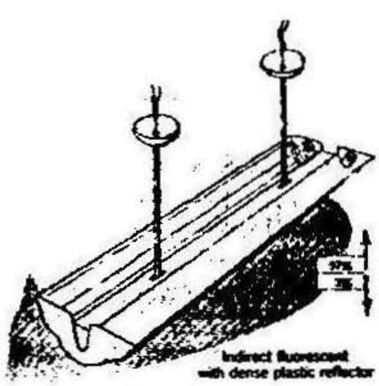
Ninety to one-hundred percent of the light output of the luminaires is directed to the ceiling and upper walls of the room. The system is called indirect because practically all of the light reaches the horizontal working plane indirectly, that is, via reflection from the ceiling and upper walls. Therefore, the ceiling and upper walls in effect become the light source and, if these surfaces have a high-reflectance finish, the room illumination is quite diffuse (shadowless). Since the source must be suspended at least 18 in. (depending on the unit's brightness) in order to avoid excessive ceiling brightness, this system requires a minimum ceiling height of (2.85 M) 9 ft. and 6 in. (See Figure below)



Indirect lighting



(A)

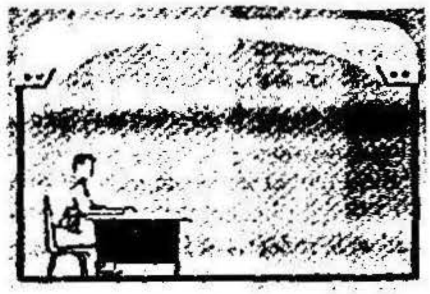


Indirect fluorescent with dense plastic reflector

In addition to diffuseness, the resultant illumination is generally uniform, and direct and reflected glare are low. A CRF in excess of 1.0 is common, with associated high ESI footcandles.

CRF - Contrast Rendition Factor
ESI - Equivalent Spherical illumination

In order to avoid an unacceptable (greater than 20:1) brightness ratio between the luminaire and its surrounding field, the luminaire is made translucent, at least on the bottom surfaces and sometimes on the sides. This type is known as "Luminous indirect" in contradistinction to metal reflectors, which are totally indirect. Architectural coves are classed as indirect lighting.



(b)

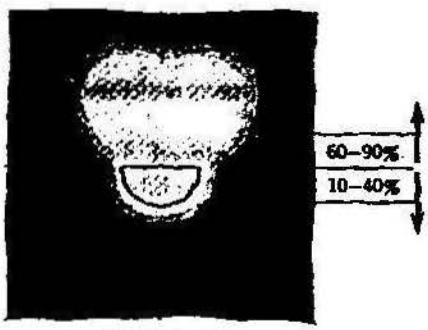
In all cases, but most particularly in the instance of high-level illumination, the luminaire spacing and suspension length and the cove or valance dimensions must be carefully chosen to avoid excessive ceiling brightness. We consider 75 raw fc to be the maximum horizontal-plane illumination attainable without exceeding ceiling brightness limits of 400 fL. With a CRF in excess of 1.0, this is sufficient for all but difficult tasks. The lack of shadow, low source brightness, and highly diffuse quality created by the indirect lighting system give a very quiet cool ambience to this type of lighted space, suitable for private offices, lounges, and plush waiting areas. Areas having specular visual tasks use this system to advantage.

When properly designed, particularly when the source of light is architectural coves, the ceiling has a floating, almost infinitely deep or skylike quality, which is pleasant and can be used to give an impression of height in a large room of low ceiling. This system is not to be confused with the self-luminous transilluminated ceiling, which is a direct lighting system of entirely different quality and effect. A further characteristic of the indirect lighting system is loss of texture on vertical surfaces as is common to all fully diffuse lighting.

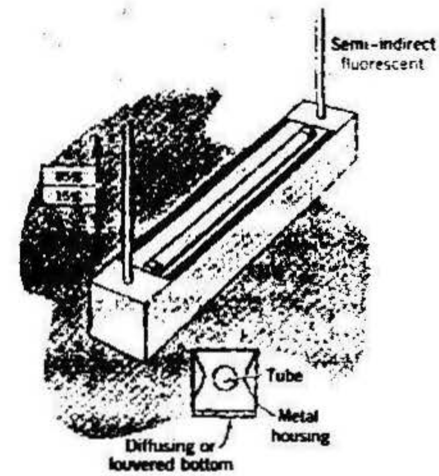
Indirect lighting is by nature inefficient, since much of the useful light reaches the working plane only after double reflection — within the fixture and off the ceiling. Although, to some extent, this is offset by the high ESI, applications to difficult seeing tasks normally require supplementary lighting. Thus an indirectly lighted drafting room having tables equipped with supplementary lamps would take advantage with both systems — the local high-intensity light at about 200 fc for the restricted area being worked on, and overall table lighting of 40 to 50 fc ESI.

2. **Semi-Indirect Lighting**

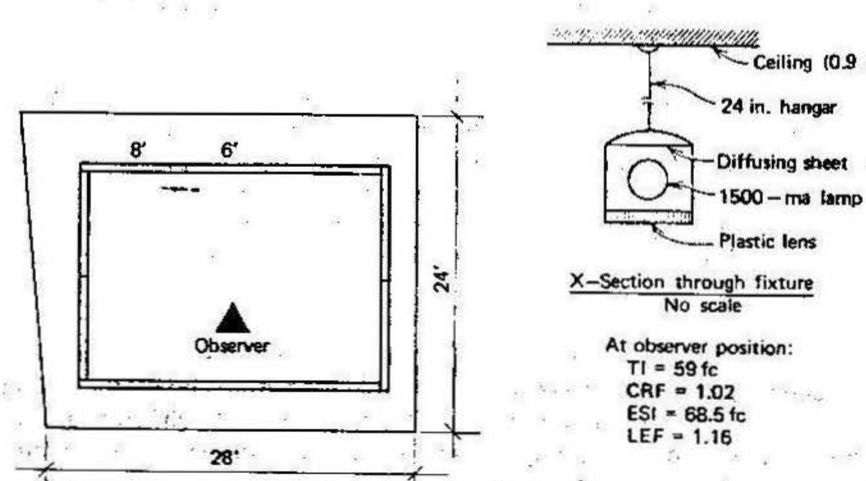
Sixty to ninety percent of the light is directed upward to the ceiling and upperwalls. This distribution is similar to that of indirect, except that it is somewhat more efficient and allows higher levels of illumination without undesirable brightness contrast between fixture and surroundings along with lower ceiling brightness. A typical fixture employs a translucent diffusing element through which the downward component shines, and is illustrated in the figure below.



Semi-indirect lighting



The ceiling remains the principal radiating source and the diffuse character fo room – lighting remains. VCP and ESI both remain high as with indirect lighting.



(a)

A CRF in excess of 1.0 is attainable, as figure as shown in. In both indirect and semi-indirect systems, it is often desirable to add accent lighting or downlighting in order to break the monotony inherent in these systems, and to establish a visual point of interest, or create required modeling shadows.

The quality of the semi-indirect system is somewhat different than indirect when using fixtures (semi-indirect cannot use architectural coves) because attention is not drawn to the fixtures, since they exhibit less contrast with the background ceiling brightness. Some of the feeling of ceiling cavity depth can be achieved by using well-shielded luminaires with luminous sides.

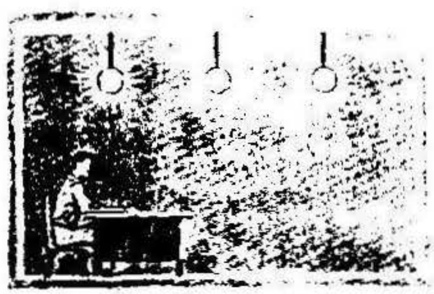
In both indirect and semi-indirect lighting systems the light undergoes a number of ceiling and wall reflections before reaching the horizontal working plane. Greater illumination can be achieved of these surfaces are colored than if they are grays of the same luminuous reflectance.

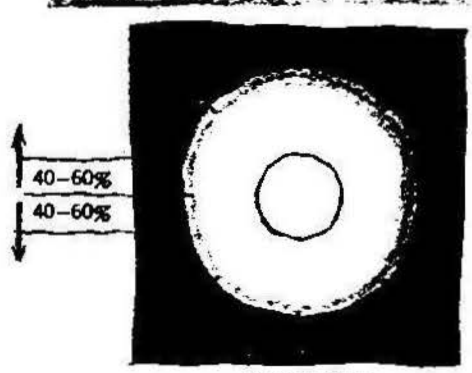
3. General Diffuse and Direct-indirect Lighting

This type provides approximately equal distribution of light upward and downward, resulting in a bright ceiling and upper wall background for the luminaire. For this reason brightness ratios in the upper — vision zone are usually not a problem, although direct and reflected glare may be troublesome at high illumination levels (100 fc and above). Since the ceiling is a major though secondary source of room ilumination, diffuseness will be good, with resultant satisfactory vertical-plane illumination. Light falling on a horizontal surface will derive principally (65 to 75%) from the luminaire and secondarily from the ceiling (25 to 35%), the exact ratio being dependent on the ceiling reflectance and the fixture characteristic.

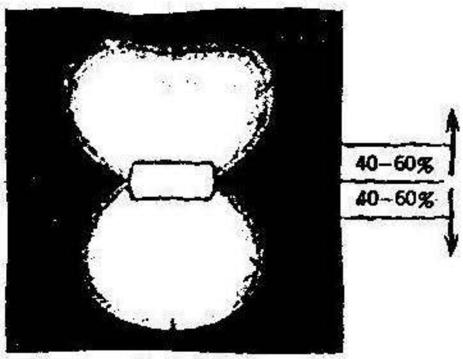
The difference between general diffuse (ex: an opal diffusing globe) and direct-indirect (ex: an open top luminuous side and bottom luminaire) lies in the fixture characteristic; diffuse fixtures give light in all directions, whereas direct-indirect have little horizontal component. Stems should be of sufficient length to avoid excessive ceiling brightness. Generally not less than 12 in. (see following figures)

General diffuse incandescent

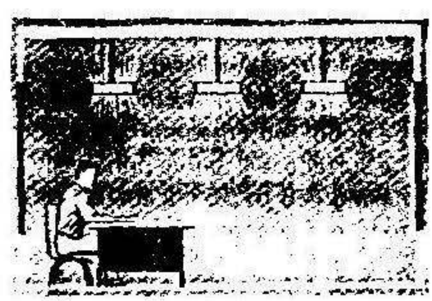


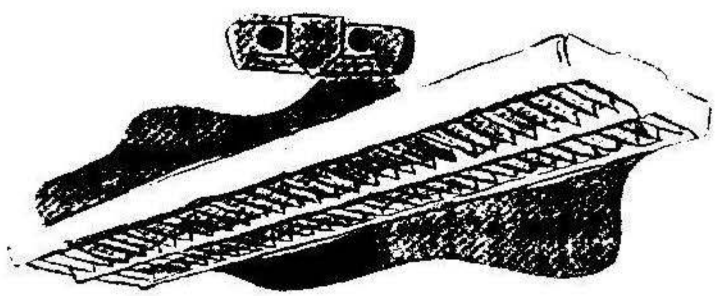


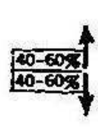
General diffuse



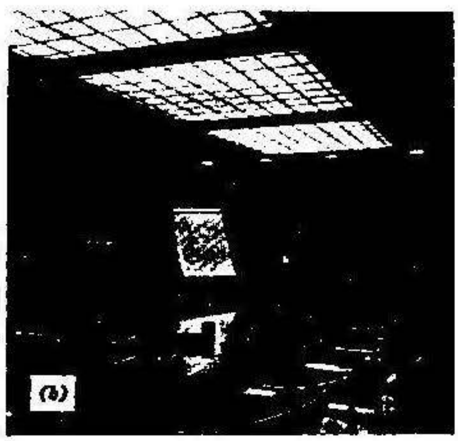
Direct-indirect




Direct-indirect fluorescent



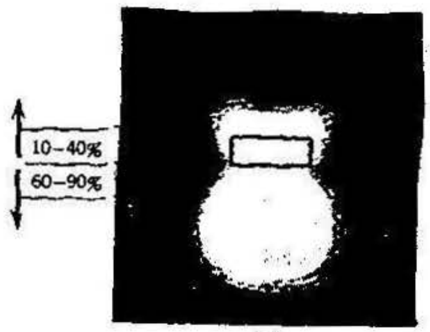
Since the impression of illumination depends to a large extent on wall brightness because this is the surface we see most often, a space with general diffuse illumination will appear lighter than one with direct-indirect because of the darker walls in the latter. This effect is most pronounced with highly directional downlights. If this effect is not desired, fixtures most be placed near the walls or other wall illumination provided.



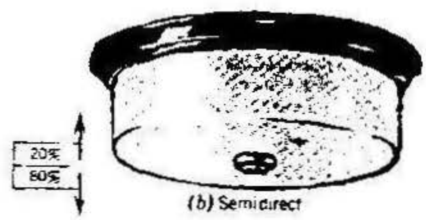
Quality of the lighting depends in large measure on the layout and on the tasks involved. By avoiding excessively bright units and giving attention to positioning of sources and viewing angles, VCP and CRF can both be kept high. Fixture brightness are interest points and the space will not appear dull and monotonous. Efficiency of these two systems is good. Both are well applied in spaces requiring overall uniform lighting at moderate levels such as classrooms, standard office work spaces, and merchandising areas.

4. **Semi-Direct Lighting**

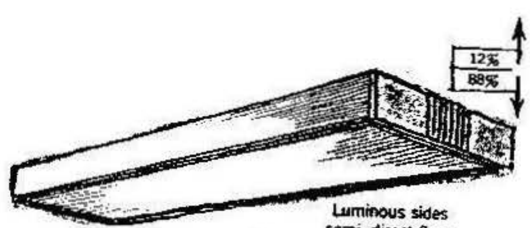
With this type of lighting system, 60 to 90% of the luminaire output is directed downward and the remaining upward component serves to illuminate the ceiling. See figure.



(a)



(b) Semidirect



(c) Luminous sides semi-direct fluor.

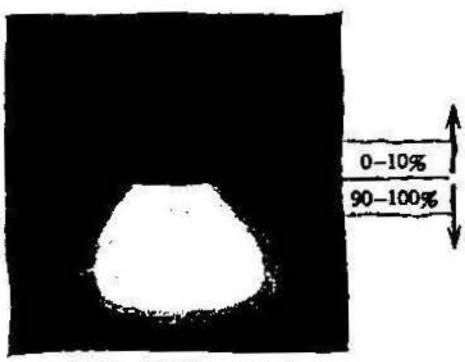
If the ceiling has a high reflectance this upward component will normally be sufficient to minimize direct glare, depending upon eye adaptation level as determined by overall illumination. The degree of diffuseness will depend in large measure on the reflectances of room furnishings and of the floor. Shadowing should not be a problem when upward components are at least 25% and ceiling reflectance not less than 70%. With smaller upward components the system is essentially direct lighting. The system is inherently effi-

cient. Reflected glare can be controlled by the methods discussed in Chapter 12, glare with adequate wall illumination, the quality of the lighting gives a pleasant working atmosphere. It is applicable to offices, classrooms, shops, and other working areas.

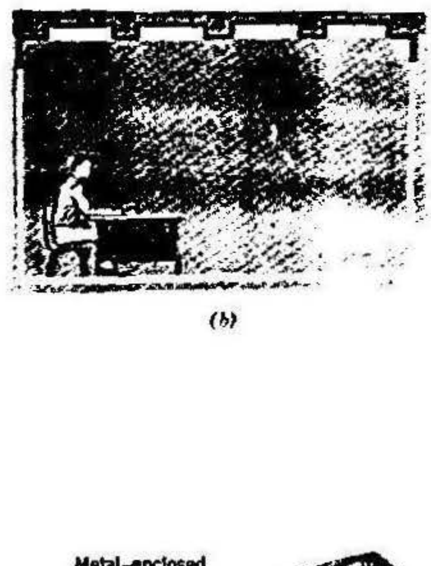
5. Direct Lighting

Since essentially all the light is directed downward, ceiling illumination is entirely due to light reflected from the floor and room furnishings. This system then, more than any other, requires a light, high-reflectance, diffuse floor unless a dark ceiling is desired from an architectural or decorative viewpoint. Occasionally the ceilings are deliberately painted a dark color and pendant direct fixtures used in order to lower the apparent ceiling of a poorly proportioned room or to hide unsightly piping, ductwork, and so on.

The effect of direct lighting depends greatly on whether the luminaires are spread or concentrating.

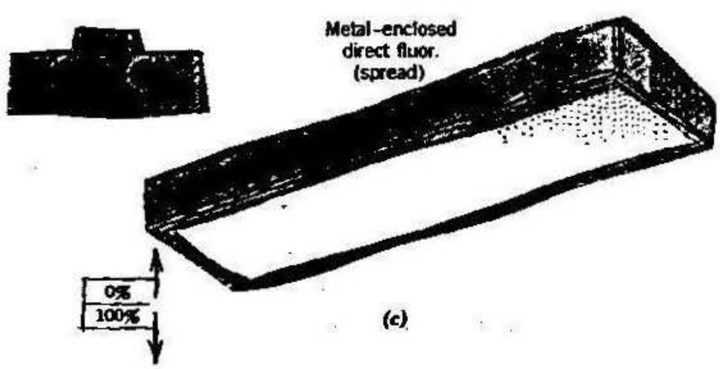


(a) Direct lighting—spread

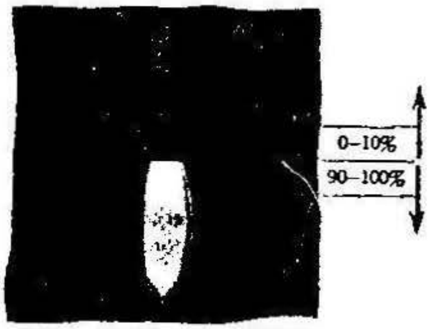


(b)

Spread-type direct lighting (a), *illuminates all room surfaces except the ceiling* (b), *which is only illuminated by reflection from the floor. Some diffuseness is evident. The most common type of unit in this category is the direct fluorescent either surface-mounted* (c) *or troffer type in a hung ceiling.*

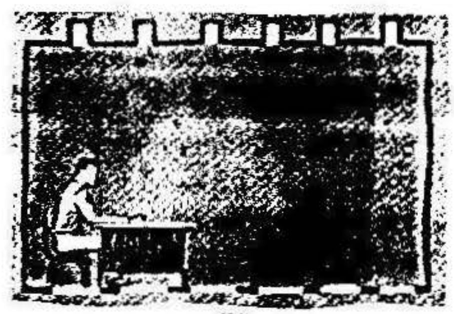


(c)

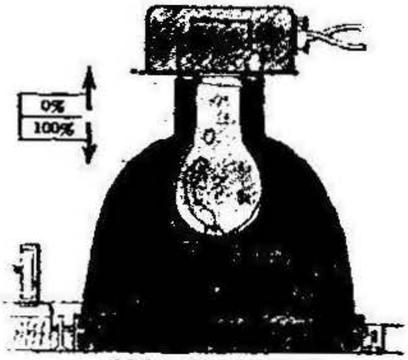


(a) Direct lighting—concentrating

With concentrating direct distribution (a), *the floor is the only luminous surface* (b), *other than the ceiling fixture. Diffuseness is absent. Walls are dark. Incandescent downlights* (c) *are of this type unless equipped with spread-type lenses.*

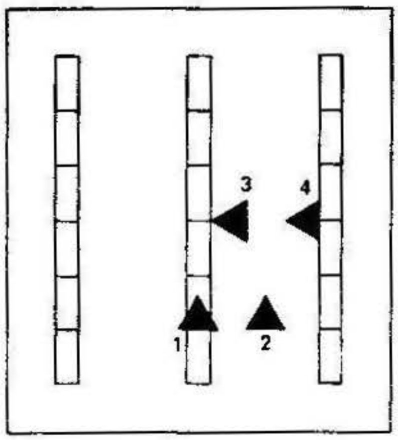


(b)



(c) Direct concentrating

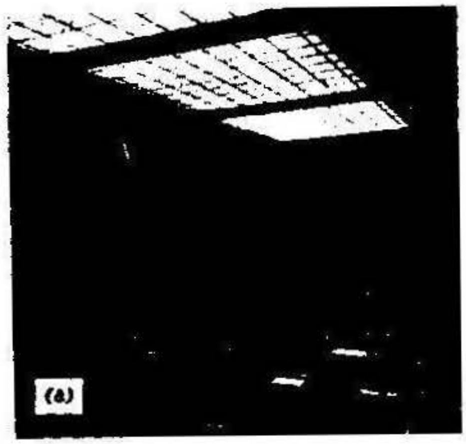
In the case of the *spread* luminaire, considerable diffusion results from reflections on floor, furniture, and walls of light emitted at high angle from the nadir (meaning, point of heavens diametrically opposite zenith or directly under observer). The result is a working atmosphere with slightly darkened walls and ceiling. This type of lighting which is most widely represented by the recessed fluorescent troffer in a suspended ceiling, is standard for general office lighting. The fixtures themselves form a ceiling surface of light and dark areas, and the quality of the entire system is pleasant. Difficulties associated with low VCP and ceiling reflections can be controlled by proper use of reflectances, use of low-brightness units, and judicious arrangement of viewing positions.

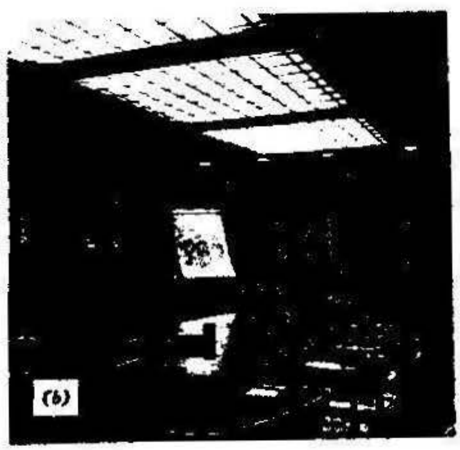


		Position			
		M1	*M2*	*M3*	*M4*
TI	2L	108	92	125	118
	4L	215	185	250	235
CRF	2L	.75	1.00	.82	1.01
	4L	.76	1.00	.83	1.03
ESI	2L	17.8	91.9	31.5	27.8
	4L	28.4	185.3	58.1	308.3
LEF	2L	.165	1.0	.25	1.08
	4L	.132	1.00	.23	1.31

TI—Task Illumination
2L—2 lamps (inside pair)
4L—4 lamps

Direct lighting gives little vertical surface illumination, requiring the addition of perimeter lighting in business atmospheres. See figure below





Concentrating downlights used alone are appropriate in restaurants and other areas where the privacy type of atmosphere generated by limited-area horizontal illumination and minimal vertical — surface illumination is desired. When these fixtures are designed with black cones or baffles or other devices that are nonreflecting at the viewing angle, the fixture appears dark. It is generally accepted that installations providing high-horizontal-surface illumination, with no apparent source of brightness such as those using black-cone downlights, are disturbing to the eye and to our normal bright-sun-and-sky orientation and should therefore be used cautiously and only in limited areas. In a lesser

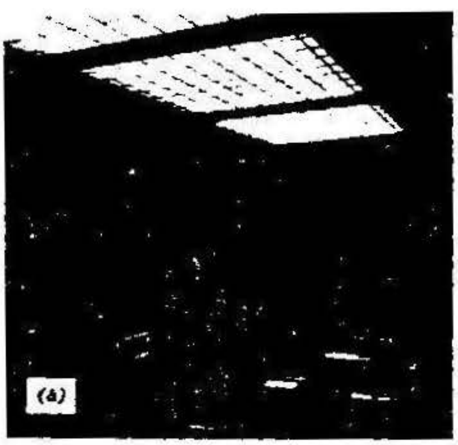
extent, this comment is applicable to very low-brightness diffusers such as the parabolic wedge type. There, however, the unit has the redeeming characteristics of low reflected glare, which is not the case with downlights.

In summary then, spread direct lighting is suitable and appropriate for general lighting while concentrating direct lighting, which reduces vertical illumination, is appropriate for highlights, local and supplementary lighting, and specialized or casual viewing.

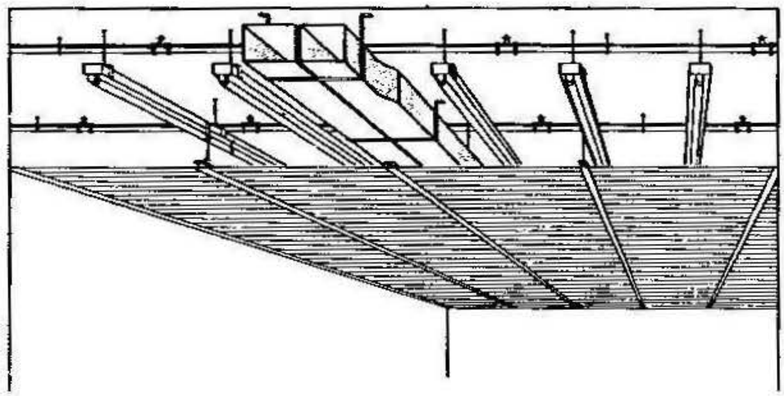
Size and Pattern of Luminances

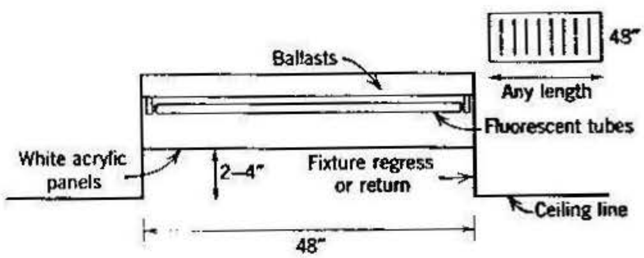
Because of its luminance each luminaires or other luminous source is a point of visual attention. To the extent that luminaires are numerous, large. Very bright, or arranged in striking patterns, attention will be drawn to them and away from other surfaces. In the absence of these characteristics it may be desirable to add accent color or accent lighting to avoid monotony. Rigid rules cannot be set down covering these criteria, but examples can demonstrate the principles.

Luminaire size should correlate with room size and ceiling height. Fluorescent fixtures larger than 2 x 4 ft. (0.60 x 1.20) should not be used in ceilings below 10 ft. (3.00 m) unless their size is minimized by some sort of surface pattern.

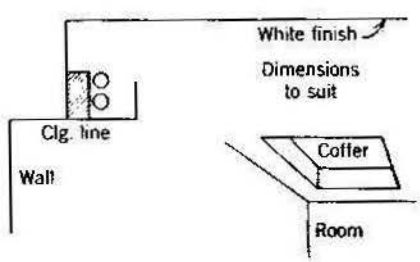


Transilluminated ceilings are all fixture and therefore require a minimum of 12 ft. mounting height. When installed below this level, particularly in large rooms, the effect is oppressive, as if the sky were lowered on us. To offset this effect, the use of colored, shaped, or dark panels is of some help. In place of a luminous ceiling, a large-area, coffer-type fixture can be utilized, which gives the impression of great depth. (see fig. below)



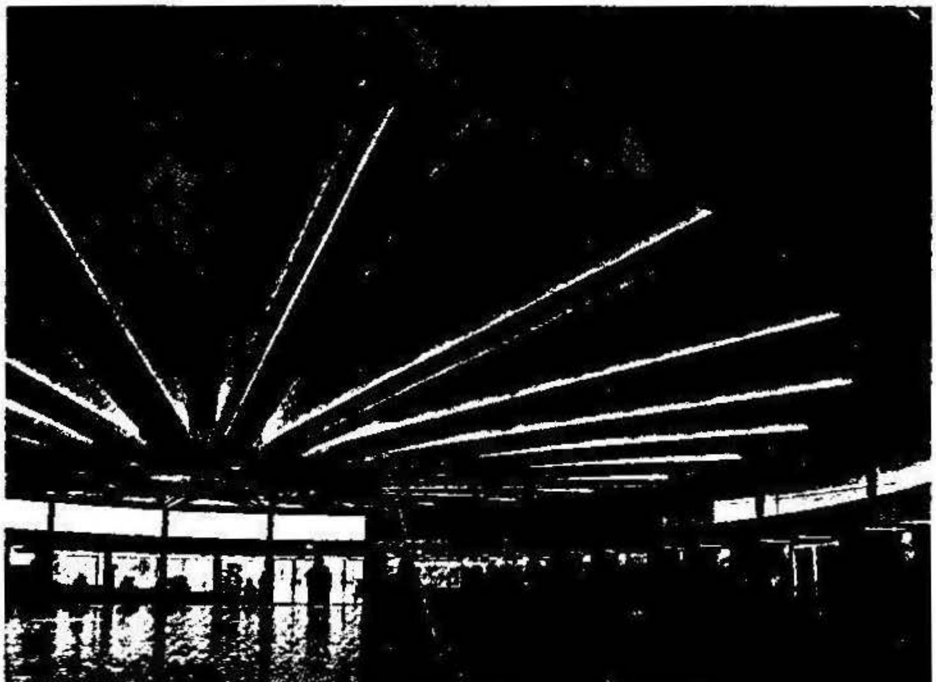


(a)

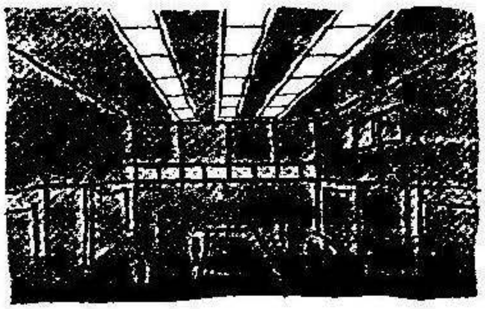


(b)

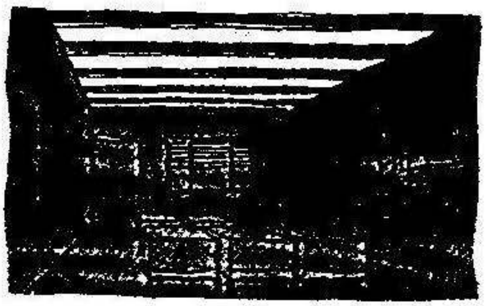
In order to achieve the uniformity of illumination necessary for general lighting, regular spacing is desirable. However, various effects may be obtained within the regularity, to accomplish an architectural purpose, is shown in the figures below and next pages. The pattern of lights must never be at cross-purpose with any dominant architectural pattern; rather it should either reinforce an architectural form to be neutral. If a strong architectural element is absent, a dominant lighting pattern may be desirable. Conversely, a strong architectural element can either be reinforced figure (a) or utilized to carry a neutral lighting pattern figure (b)



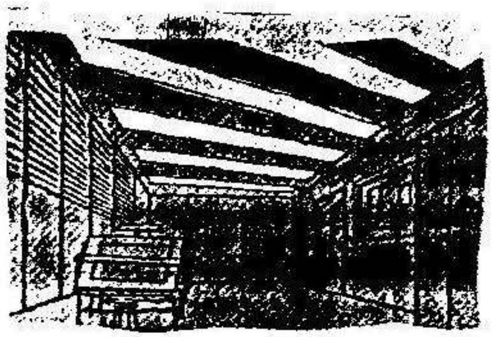
Treatment of dominant architectural patterns. In each case the lighting designer was faced with essentially the same problem, viz., a low-level seeing task in a large space with a dominant architectural ceiling. Different solutions were arrived at, each of which is consonant with the architectural ceiling. Both accomplish this by following the dominant line; *(q)*, next page, follows it with a neutral pattern.



(a) Longitudinal lines increase apparent length, direct traffic flow, decrease direct glare

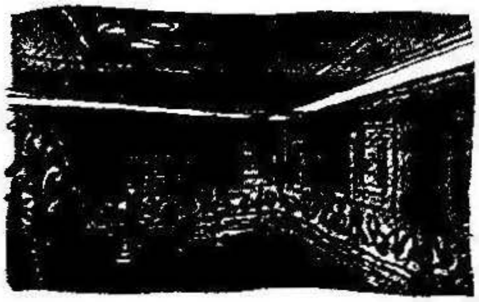


(b) Horizontal lines create a plane, increase apparent width but also increase direct glare

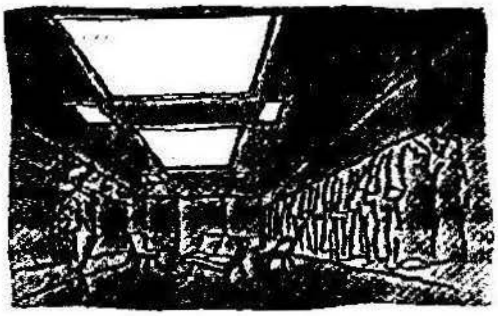


(c) Diagonal lines minimize shadows and break rectangular patterns. They are architecturally dominant

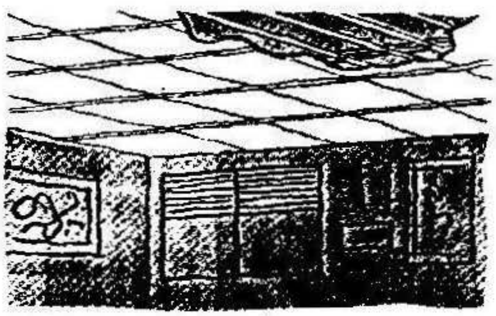
(d) **Rectangular pattern is architecturally dominant and therefore must be used carefully. It is a poor choice in stores where attention downward is desired**



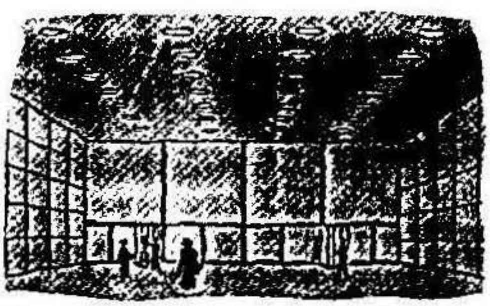
(e) Cornices, valances and coves are luminous ceiling borders. In large rooms suspended coves achieve uniform ceiling brightness and when designed with a downward component or combined with local lighting, as illustrated, give a pleasant, intimate atmosphere



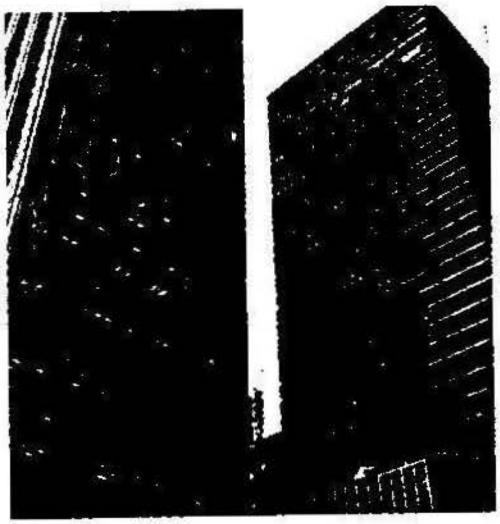
(f) Coffers create a decorative architectural effect and can be designed to resemble skylights or can be built into actual skylights



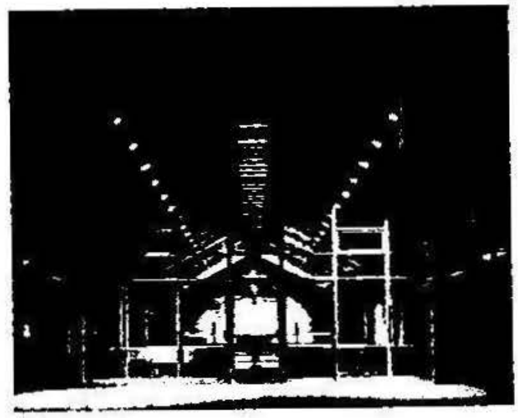
(g) Luminous ceiling system utilizing louvers or translucent material suspended beneath rows of fluorescent lamps provides high illumination, low brightness and high diffusion. The system is architecturally oppressive, and monotonous, requiring some accent of either color or lighting



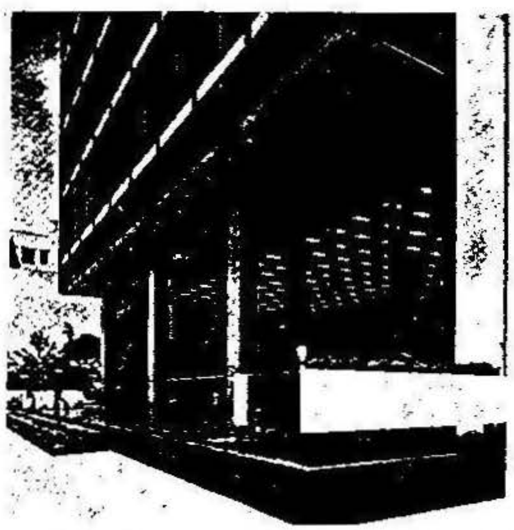
(h) Downlights are architecturally neutral and may therefore be spaced evenly .... (j) or unevenly



That patterns of lighting are plainly visible even during the daytime is apparent from this photo. The attractiveness of uniformity of fixture pattern can readily be seen. Photo by Stein.



Lighting can be utilized as a medium to connect the inside and outside of a building. The simple expedient of continuing the lighting pattern beyond the window or wall glass provides visibility from inside out as well as outside in. Care must be exercised to avoid fixture placement which will reflect in the glass.



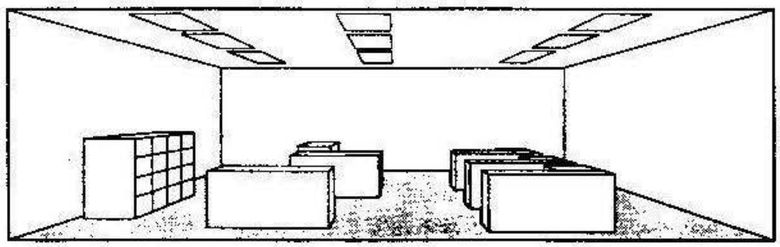
Since fixtures are readily visible even when unlit during daylight hours, their outline can be accentuated and the resultant pattern utilized as an architectual motif.

The large can-shaped surface-mounted downlights dominate the area's appearance despite the high ceiling. The pimpled look could be eliminated by recessing the units. Or, taking advantage of the prominence of these units, interest could be added by altering the regular pattern.

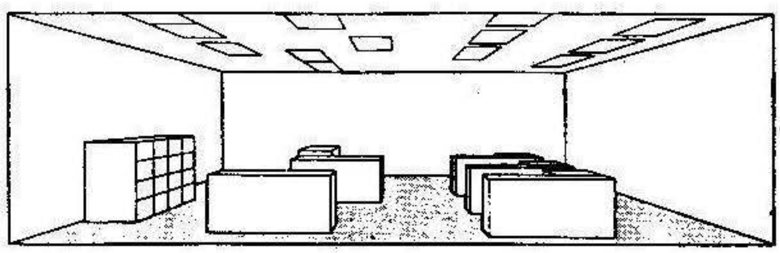
The lighting in this extremely strong architectural pattern was hormonized deftly by recessing fixtures deeply into the lattice motif. Metal halide HID units and tungsten-halogen units were used.

The lines of lights in the center converge optically to produce a directional flow of traffic toward the escalator. The remaining floor lighting is provided by visually pleasing circular patterns around columns

Generally, continuous row installations are more attractive than individual units, and eliminate the dominating checkerboard effect of the latter. Coves and cornices give the ceiling a floating or light effect. Geometric patterns can be used to add interest or break monotony of large areas; such as department stores. Generally, incandescent downlights are not dominant. and regularity of placement is not essential. Nonuniform layouts with large sources create a distinct pattern problem in as much as they are too large to be neutral, and the nonuniformity can create visual confusion (see figure below)



(a)



(b)

The only cure for this problem is to minimize the source brightness by using low-brightness diffusers. The incorporation of daylight into the luminous sources of a space should take cognizance of size and pattern as well. Large windows are not consonant with small ceiling sources, whereas skylights are readily integrated with other ceiling units. A frequently neglected consideration is the appearance of a source when de-energized. With proper daylight and energy-conserving design, many sources will be "dark" during the normal — use hours of the spaces. Obviously, low-brightness sources will change least in appearances, which is a factor in their favor.

15

DETAILED LIGHTING DESIGN PROCEDURE

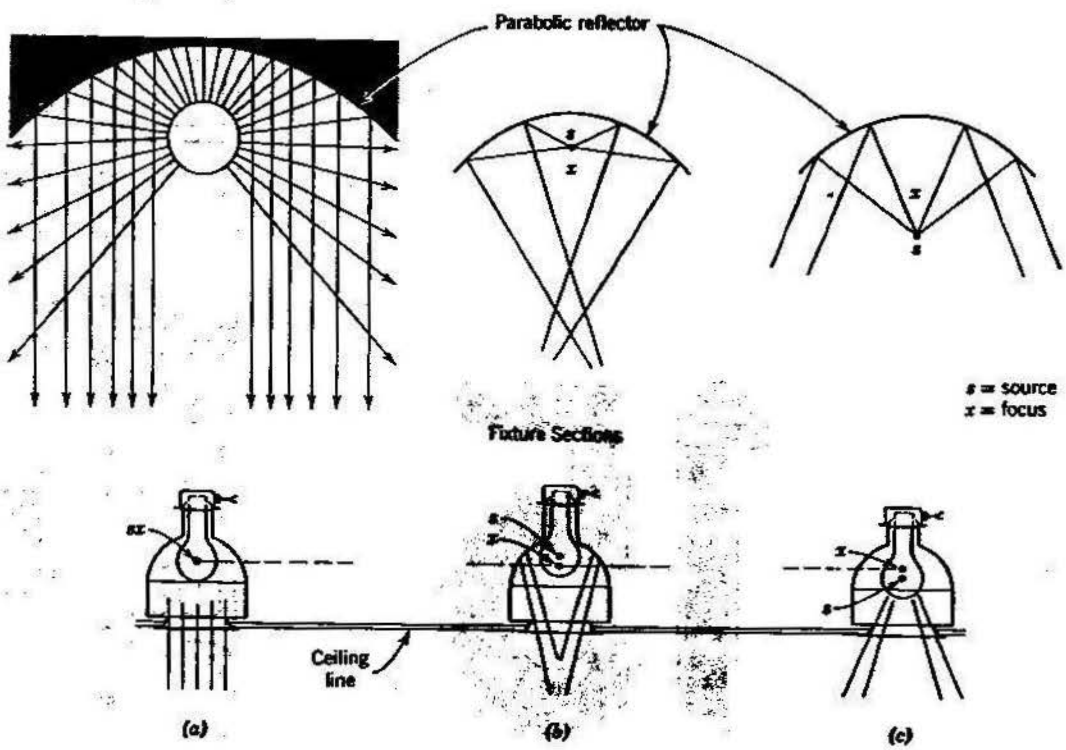
DETAILED LIGHTING DESIGN PROCEDURES

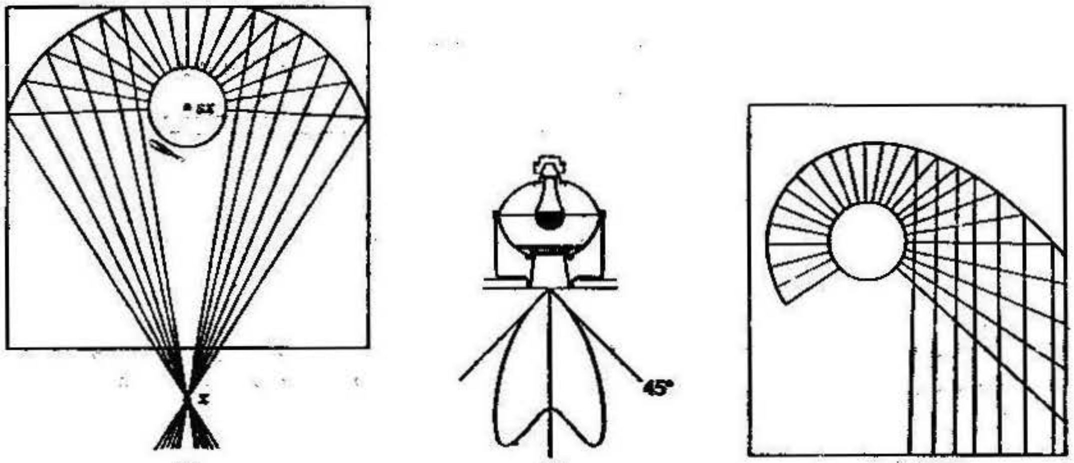
DESIGN DECISIONS

Refer again to the figure on lighting design procedure chart, chapter 14; at this point in the design process the lighting hardware is chosen on the basis of the considerations adduced in the preliminary design stage and the appropriate calculations performed. Some spaces will require overall, uniform illumination other spaces will utilize local lighting alone (or local lighting in addition to general). requiring point-by-point illumination calculations or some other method for restricted—area calculation. Part of these calculations are those VCP and ESI either exact or estimated. Additional considerations at this design stage are type of ceiling system, for example, modular, movable fixture, and integrated s rvice, and ancillary considerations of ballast noise, fixture heat distribution, brightness ratios and maintenance. Also decided here is whether to utilize work station mounted or built-in lighting, both of which are principally applicable to open-plan spaces.

Direct — Lighting Luminaire Characteristics

It is important to understand the action of luminaire reflectors. The basic shapes and beam patterns are illustrated in these following: figures (1), (2), (3), (4), whilsielding methods are shown in figure (5).

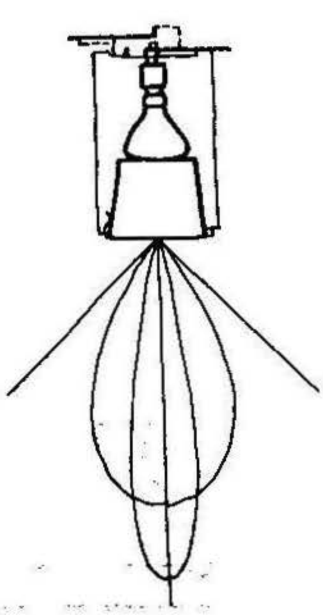


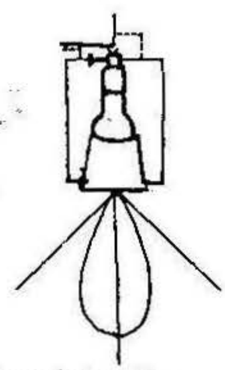


(a) *(b)* *(c)*

(a) Fixture shows lighting distribution for both spot and flood lamps. In normal ceiling heights their circular pattern can be seen on the floor.

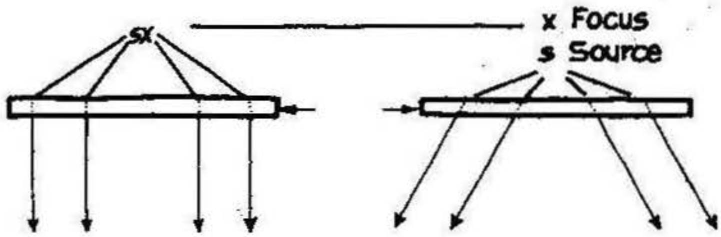
(c) Wall washing device of high intensity useful for accenting walls.



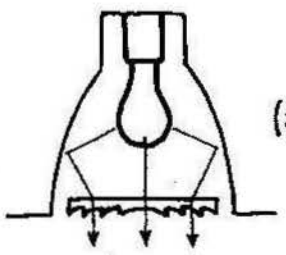


(b) Low intensity downlight, useful for low-level mood lighting,

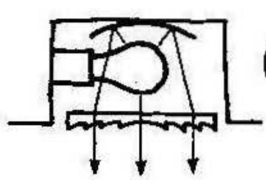
Ray Diagrams



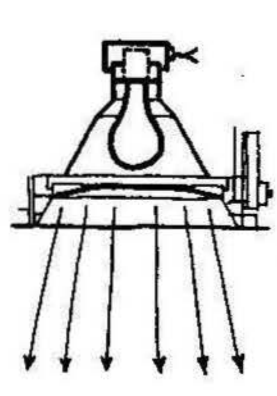
By utilizing a lens fixture, a smaller housing without a reflector can be used, while still maintaining beam control



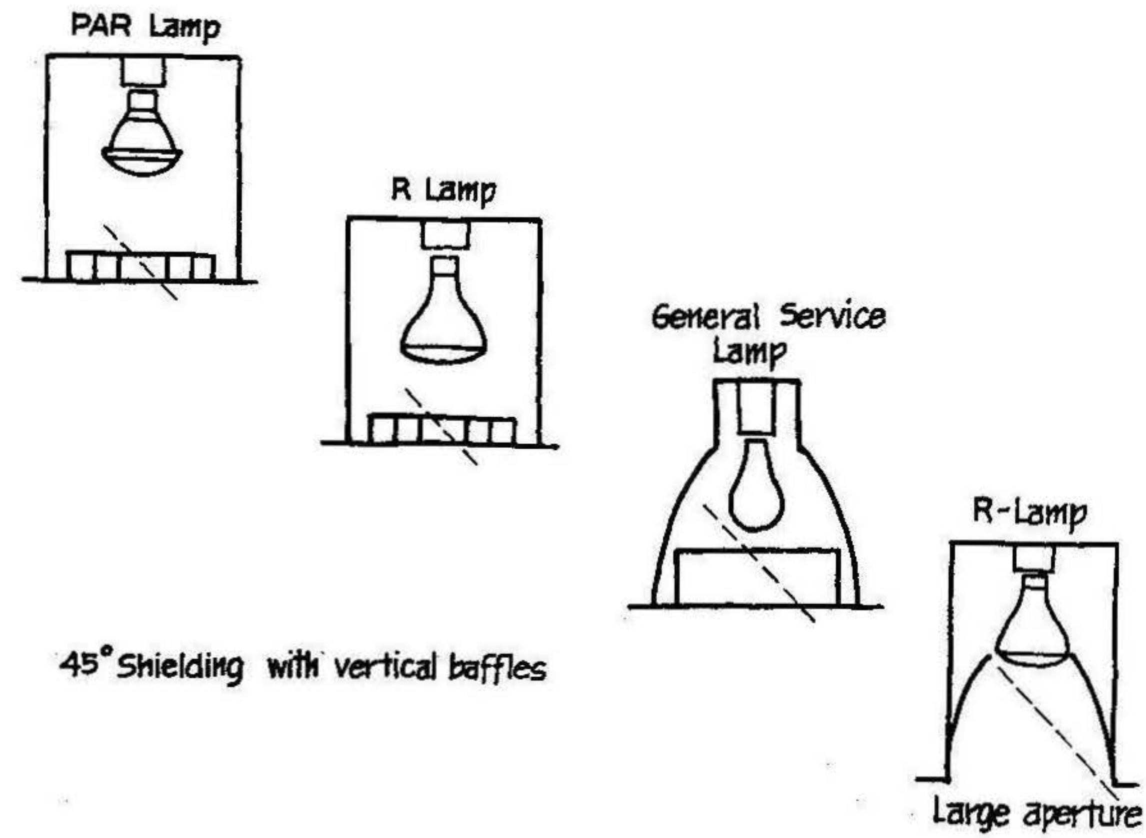
(a)



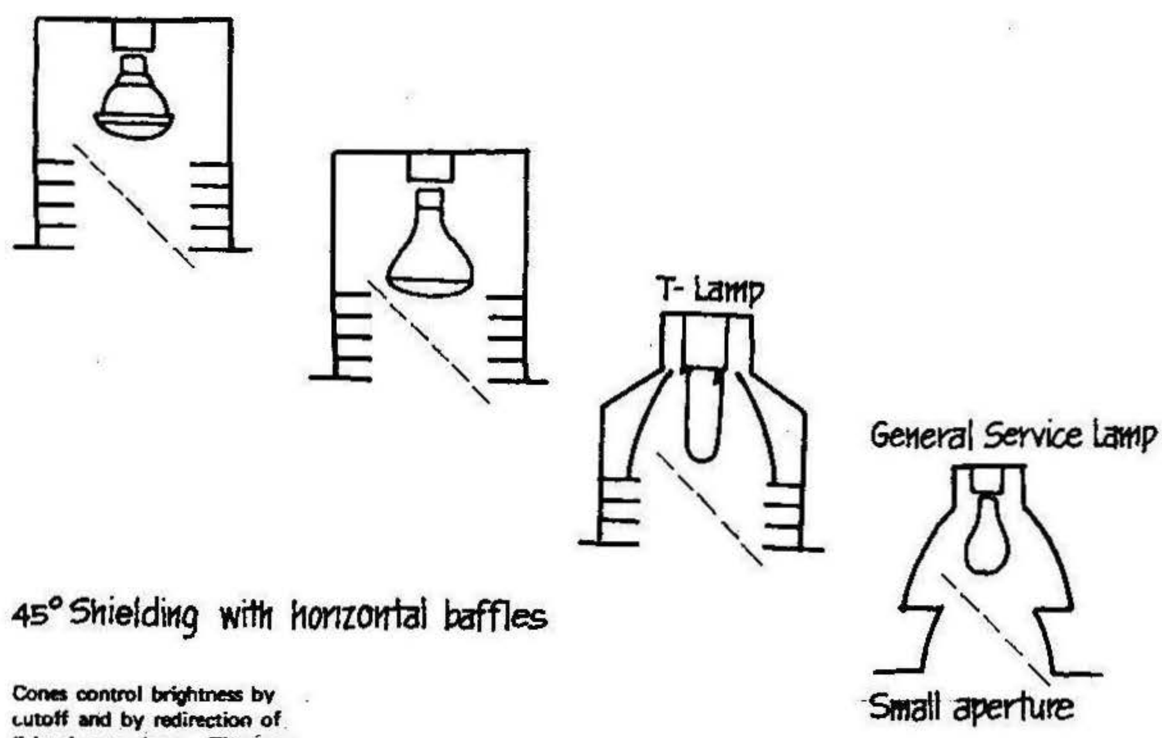
(b)



(c)



45° Shielding with vertical baffles



45° Shielding with horizontal baffles

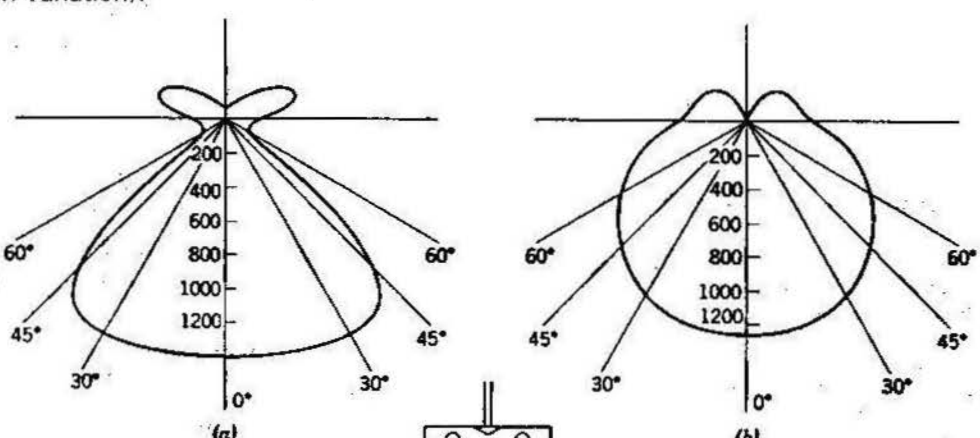
Cones control brightness by cutoff and by redirection of light due to shape. They are either parabolic or elliptical. A light specular finish appears dull; a black specular finish appears unlighted.

Black finishes require high quality maintenance since dust shows as a bright reflection.

Although the illustrations use point sources (incandecent or HID lamps), the principle illustrated is applicable to reflectors for linear (fluorescent) sources, when considered in section. (see figure also on design features of recessed luminaires on chapter 16). An interesting development in the area of elliptic reflectors was produced recently by one of the major lamp manufacturers. Note from figure 2(a) and (b) that the so-called pin-hole downlight requires an elliptic reflector to focus the light through this hole at point "x" in order to maintain even minimal fixture efficiency. Elliptic reflectors are large and frequently space above the ceiling is too restricted for their use. A lamp with an integral elliptical reflector, which can therefore be utilized in a standard baffled reflector without severe losses, is illustrated in this figure.

Lighting Fixture Distribution Characteristics

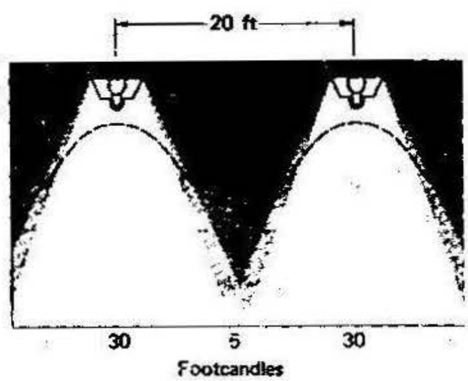
The two distribution curves shown in the figure below are actual test results of two-2-lamp 1 ft. wide by 4 ft. long, semi-direct fluorescent fixtures with prismatic enclosures. The flat bottom of curve (a) indicates even illumination over a wide area and therefore a high spacing to mounting height ratio (1.5), whereas the rounded bottom of curve (b) indicates uneven illumination and closer required spacing for uniformity (1.2 ratio of spacing to mounting height above working plane for a maximum of 20% illumination variation).



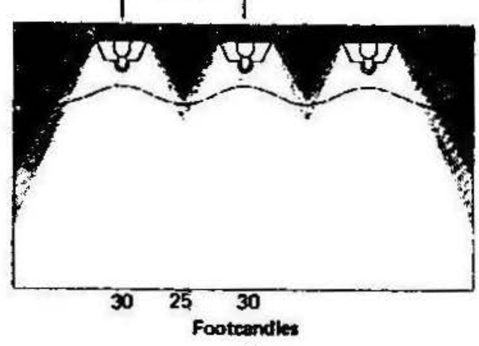
The straight sides of curve (a) show a fairly sharp cutoff, and the small amount of light above 45° means high efficiency, sufficient wall lighting, adequate diffuseness and very little direct glare problem, but a distinct possibility of veiling reflections. Conversely, curve (b) shows a large amount of horizontal illumination (above 45°), with resultant direct glare, diffuseness, and relative inefficiency, since horizontal light is attenuated by multiple reflections before reaching the horizontal working plane. Here, however, low output below 45° minimizes reflected glare. The uplight component of fixture (a) is directed outward to cover the ceiling and will not cause hot spots; the corresponding light from fixture (b) is concentrated above the fixture and will give uneven illumination of the ceiling. Thus, we see that a rapid inspection of a fixture curve performed by an informed person can yield a large amount of data or the fixture's performance.

Uniformity of Illumination

In any space intended to be lighted uniformly with multiple discrete ceiling—mounted light sources (rather than a luminous ceiling), it is necessary to establish a fixture spacing that will give acceptable uniformity of illumination. A ratio of maximum to minimum illumination on the working plane of 1.2 is readily acceptable and 1.3 is tolerable. For general background or circulation lighting, up to 1.5 is acceptable. The data given by manufacturers (see figures immediately above the distribution curves for each fixture in the table coefficients of utilization in the next coming pages) are generally based on this 1.2 figure, which should not be exceeded in a quality design. See figure below.



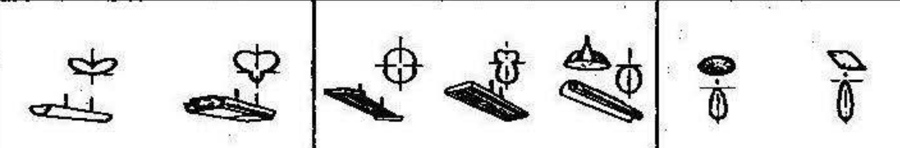
(a)



(b)

We mentioned above in the distribution characteristic that the fixture of figure (a) had a high spacing to mounting—height ratio because of its flat bottomed curve. This ratio, when not given by the manufacturer, may be approximated from the figures in the table below.

Spacing and Mounting-Height Relationship of Luminaires for Illumination Uniformity[a]

	Light Distribution							
	Indirect		*Semi-indirect*	*General Diffusing*	*Direct-Indirect*	*Spread Direct*	*Semiconcentrating Direct*	*Concentrating Direct*
								
Ceiling Height	*Distance[b] from Walls*	*Length of Suspension*	*Maximum[c] Spacing of Luminaires*	*Mounting[d] Height of Luminaires*	*Distance[b] from Walls*	*Maximum[c] Spacing of Luminaires*	*Maximum[c] Spacing of Luminaires*	*Maximum[c] Spacing of Luminaires*
8	2	•	9	8	2	7½	5½	2½
9	2		10½	9	2	9	6	3
10	2½		12½	10	2½	10½	7	4
11	2½		13½	11	2½	12	8	4½
12	3		15	12	3	13½	9	5
13	4		17	13	4	15	10	5½
14	5		19	14	5	16½	11	6
15	5		20	15	5	18	12	6½
16	6		22	16	6	20	13	7
18	6		24	18	6	22	15½	8
20 or more	7		28	20 or more	7	25	17½	9

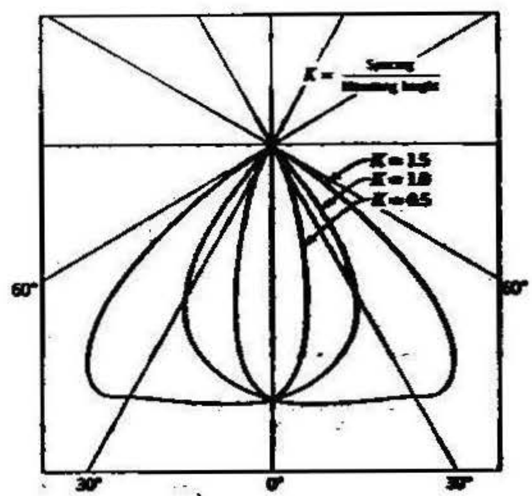
[a] All dimensions in feet.

[b] These spacings apply where desks and benches are next to wall, otherwise one-third the spacing between units is satisfactory.

[c] The actual spacing of luminaires is usually less than the maximum spacing to suit bay or room dimensions.

[d] For mounting height of general diffusing and direct-indirect fixtures.

The distribution types shown in this table are generic and therefore may not be readily applicable in some cases. The curves in the figure below are an approximation for direct distribution incandescent fixtures.



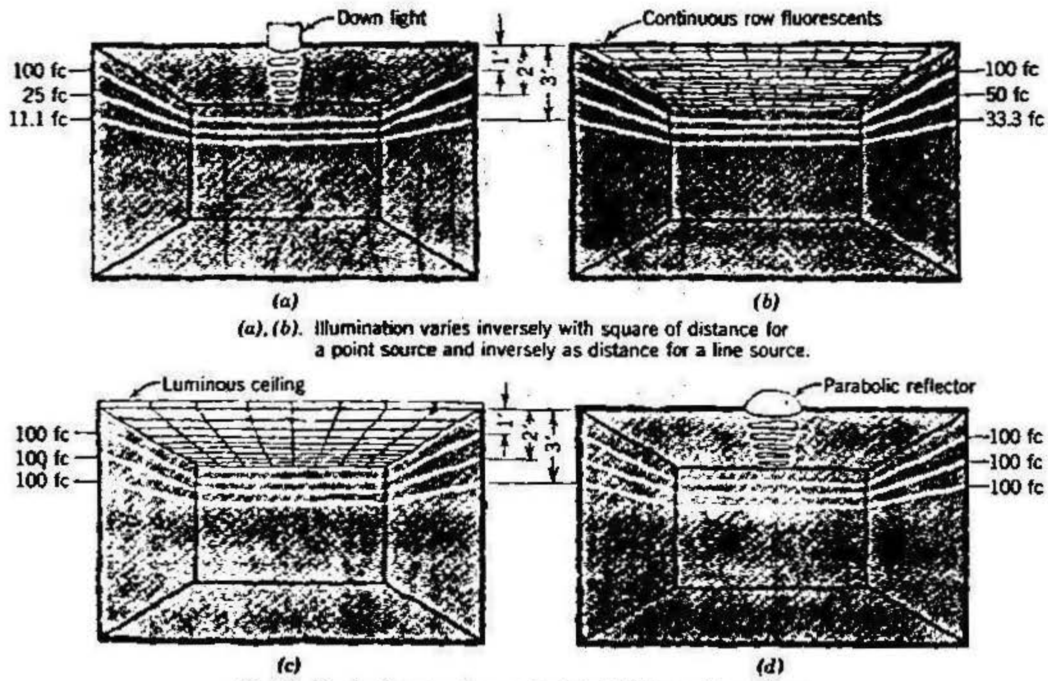
It is well known that illumination levels near walls drop off at least 30% even in a well — designed installation. To counteract this effect, particularly when placement of furniture is such that visual tasks will occur near walls, the designer should arrange to provide additional illumination in these areas. This may readily be accomplished by additional fixtures, higher-output units, perimeter lighting, or some type of wall washing arrangement. Particular stress should be placed on this type of local lighting where wall reflectances are low, such as at walls covered with book shelves, equipment racks, low-reflectance paint, or dark wood paneling. Fixture end should be no more than 1 ft. and fixture sides no more than 2 ft. from walls.

The foregoing discussion of illumination uniformity concerned itself with uniformity on a horizontal plane. Ocassionally, it is necessary to know the degree of uniformity vertically (on horizontal planes at different elevations) Four different lighting situations are normally encountered.

They are:

a. Ploint sources such as incandescent downlights.
b. Line sources such as continuous – row fluorescent fixtures,
c. Infinite sources such as luminous ceilings whether transilluminated or indirect.
d. Parabolic reflector beams such as from PAR lamps.

The vertical uniformity of each type shown graphically in this figure.

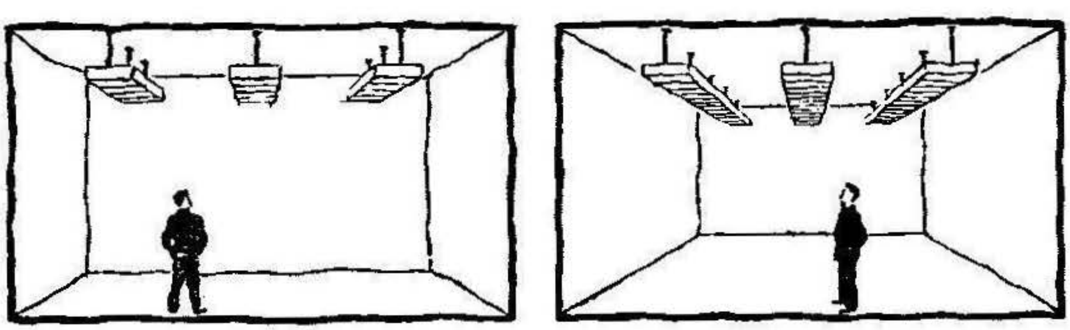


(a), (b). Illumination varies inversely with square of distance for a point source and inversely as distance for a line source.

(c), (d) Illumination remains constant at all distances from either an infinite (or nearly) source or a parabolic reflector.

Luminaire Mounting Height

The mounting height of luminaires is normally established before spacing, and uniformity requirements govern spacing as explained above. In arriving at a mounting height for fixtures with an upward component, a balance must be struck between the requirement of low-ceiling brightness and good utilization of light (low mounting) and the reticence to dominate an area, particularly a large room by using such a low mounting height that the apparent ceiling height is affected. See figure below:



Ceiling Height (Feet)	Room Width (Feet)	Hanger Length (Inches) [b]Offices and Classrooms	Hanger Length (Inches) Drafting Rooms	Ceiling Height (Feet)	Room Width (Feet)	Hanger Length (Inches) [b]Offices and Classrooms	Hanger Length (Inches) Drafting Rooms
	7	*	*		13	21 or 24	24
7	14	*	*	13	26	21 or 24	24
	28 and up	*	*		52 and up	21 or 24	24
	8	*	6		14	30	30
8	16	*	6	14	28	24	24
	32 and up	*	6		56 and up	24	24
	9	6	12		15	36	36
9	18	6	12	15	30	30	30
	36 and up	*	6		60 and up	24	24
	10	18	21		16	42	42
10	20	12	18	16	32	36	36
	40 and up	6	12		64 and up	30	30
	11	21	21		18	42	42
11	22	18	21	18	36	36	36
	44 and up	12	18		72 and up	30	30
	12	21	21 or 24		20	54	54
12	24	21	21 or 24	20	40	42	42
	48 and up	21	21 or 24		80 and up	36	36

Lighting Fixtures

The architect should consider that lighting fixtures constitute 25 to 30% of the electrical budget or 4 to 5% of the overall building budget, to appreciate their importance. Since the difference between a quality unit and an inferior one is often not readily visible to the casual observer, particular care must be taken in the specification of lighting fixtures and in examination of shop drawings and samples. All fixtures if applied properly will give a sufficient quantity of light, but only a good unit will combine quantity with good quality, ease of installation, facility of maintenance and indefinite life. In addition, regardless, of the manufacturing details of a lighting fixture, installation procedure must be proper to insure mechanical rigidity and safety, freedom from excessive temperatures, and requisite accessibility of component parts and of the fixture outlet box.

Lighting Fixture Construction

(a) All fixtures shall be wired and constructed to comply with local codes.

(b) Fixtures shall generally be constructed of 20 gauge (0.0359 in.) thick steel minimum. Cast portions of fixtures shall be no less than 1/16 in. thick.

(c) All metals shall be coated. The coating shall be a baked — enamel white paint of minimum 85% reflectance, on top of a rust-inhibiting priming process. Unpainted surfaces shall be finished with a clear lacquer except for anodized or "ALZAC" surfaces. All hardware shall be cadmium-plated of otherwise rust-proofed.

(d) Lampholders in incandescent fixtures shall be porcelain, with nickel plated screw shell

(e) An incandescent fixture shall not cause a temperature exceeding 90° on any outside surface.

(f) No point on the outside of a fluorescent fixture shall exceed 90°.

(g) Each fixture shall be identified by label carrying the manufacturer's name and address and the fixture catalogue number.

(h) Glass diffuser panels in fluorescent fixtures shall be mounted in a metal frame. Plastic diffusers shall be suitably hinged. "Lay-in" plastic diffusers should not be used,

(i) Plastic diffusers should be of the slow-burning or self-extinguishing type with low smoke density rating and low heat distortion temperatures. This latter shall be low enough so that the plastic diffuser will distort sufficiently to drop out of the fixture before reaching ignition temperature,

(j) It is imperative that plastics used in air-handling fixtures be of the noncombustible, low-smoke-density type. These requirements also apply to other nonmetallic components of such fixtures.

(k) All plastic diffusers shall be clearly marked with their composition material, trade name, and manufacturer's name and identification number. The characteristics of many plastic diffusers change radically with age and exposure to ultraviolet light. Glass and acrylic plastic are stable in color and strength. Other plastics may yellow and even turn brown thus, diminishing light transmission radically as well as changing the fixture appearance. Some plastics that are initially very tough and "vandalproof" embrittle with age and exposure to weather or the ultraviolet light of a mercury or fluorescent source. Thus, the long-range as well as initial characteristics of all diffuser elements must be investigated before specification approval.

(l) Ballasts shall be mounted in fixtures with captive screws on the fixture body, to allow ballast replacement without fixture removal.

(m) All fixtures mounted outdoors, whether under canopies or directly exposed to the weather, shall be constructed of appropriate weather — resistant materials and finishes, including gasketing to prevent entrance of water into wiring, and shall be marked by the manufacturer, "suitable for outdoor use".

Lighting Fixture Installation

(a) Fixtures may not be used as a conductor raceway unless specifically so designed and labeled by the manufacturer.

(b) Fixtures mounted on combustible surfaces shall not subject these surfaces to a temperature exceeding 90 °C, in a 40 °C ambient space. To this end insulating-material spacers or simply an air space may be used.

(c) Although most codes allow fluorescent fixtures less than 40 lb in weight to be mounted directly on the horizontal metal members of hung-ceiling systems experience has shown that vibration, member deflection, routine maintenance operation on equipment in hung ceilings and poor workmanship can cause such fixtures to fall, endangering life. It is strongly recommended that all fixtures, surface, pendant or recessed, whether mounted individually or in rows, must be supported from the black channel iron supporting the ceiling system (purlins) or directly from the building structure, but in no case by the ceiling system itself. This is particularly important in the case of an exposed "Z" spline ceiling system.

(d) Fixtures installed in wet plaster ceilings shall utilize plaster frames installed for that purpose.

(e) Fixtures installed in bathrooms shall not have an integral receptacle and when installed on walls shall have nonmetallic bodies. These are safety precautions.

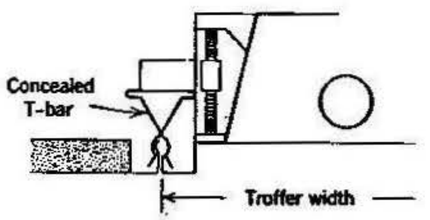
(f) The voltage to ground on branch circuits supplying lampholders and lighting fixtures shall bot exceed 150 v except for:

1. Mogul-base lampholders mounted not less than 8 ft. above the floor, and accessible only to authorized personnel.
2. Fluorescent lamp fixtures, permanently installed with appropriate ballasts, in which case the voltage may be up to 300 V. Such fixtures may not have integral switching but must use wall switches. This rule allows the use of 277 V fluorescent and mercury lighting. Use of lighting circuits above 150 V is not permitted in residences.

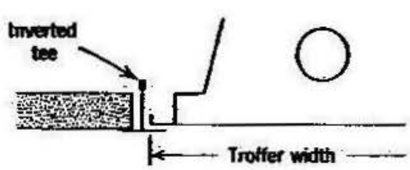
Standards for Recessed Fluorescent Luminaires

The prevalence of fluorescent troffers, that is, fluorescent fixtures recessed into a suspended-ceiling system, has necessitated industry standardization to reduce fixture — ceiling incompatibility.

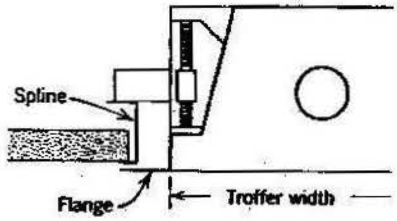
The FIVE types are shown in these figures.



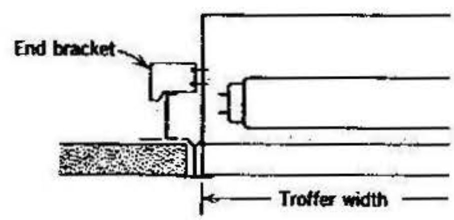
luminaire is one having vertical turned-up edges which are parallel to the lamp direction and intended to "snap-in" or otherwise align the luminaire with a concealed T-bar suspension system, the center opening of the Tees being located on modular or other symmetrical dimensional lines.



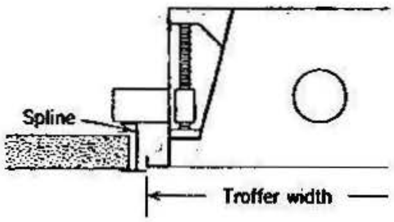
luminaire is one having edges which are designed to rest on or "lay-in" the exposed inverted T of a suspension system (customarily described as a grid ceiling system) with the webs of the Tees being located on modular or other symmetrical dimensional lines.



luminaire is one having horizontal flanges which are parallel to the lamp direction and designed to conceal the edges of the ceiling opening above which the luminaire is supported by concealed mechanical suspension.



luminaire is one having end brackets, hooks or other attachments and designed to be supported at the ends by "hooking-on" to some member of the ceiling suspension system.



Type S luminaire is one which is designed for mechanical suspension from exposed splines and dependent on splines parallel to the lamp direction for concealment of the edges of the luminaire.

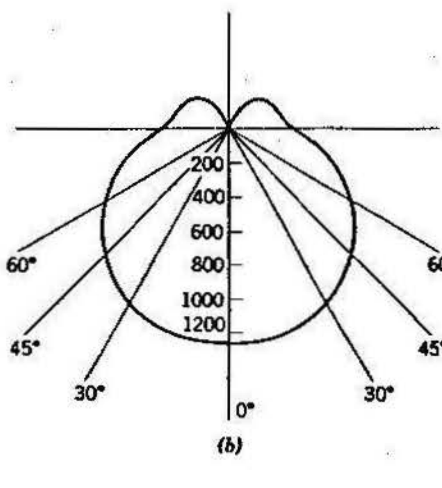
Type HS luminaire is a Type H luminaire having edges parallel to the lamp direction and dependent on splines of the ceiling suspension system for concealment of the edges of the luminaire.

Type HF luminaire is a Type H luminaire having edges parallel to the lamp direction and designed to conceal the edges of the ceiling opening in which the luminaire is recessed.

Luminaire Diffusing Elements

The diffusing elements usually considered include white plastic, striped and prismatic glass, prismatic plastic, high-reflectance aluminum (alzac), baffles, and miniature eggcrate louvers. In addition to these types there are various sizes and shapes of metal and plastic louvers and baffles, white glass, ribbed glass, etc. Each of these diffusers must be considered on its merits and a decision arrived at (60 to next line) based on photometric characteristics, cost ease of maintenance, apperance, and fire safety. A rapid review of the photometric characteristics of this most important element of a lighting fixture yields the following:

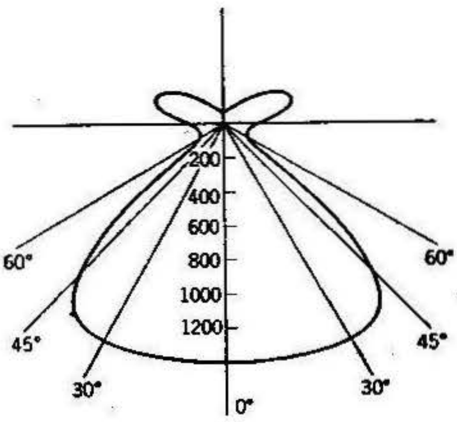
(a) **Plain White Diffusers**
These have a circular distribution giving equal light in all directions. Diffusion is good, VCP is poor, and ESI is generally poor.



(b)

(b) **Prismatic Lens**

There are dozens of designs that vary one from another considerably. The figure can be taken as typical of this genre. They produce good diffusion, high VCP and fair ESI, depending on viewing angles and positions.



(a)

(c) **Louvers and Baffles**

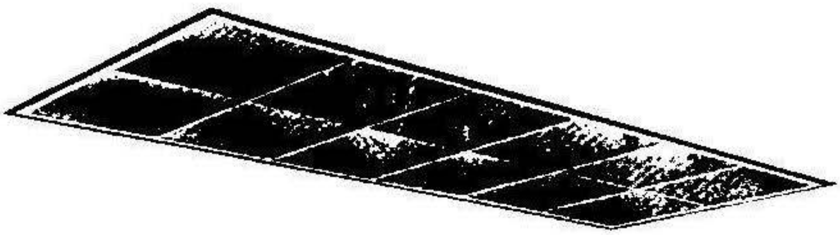
These are made of metal or plastic, in various shapes and sizes. They generally have circular to egg-shaped distribution, providing good diffusion, good VCP and poor ESI.

(d) **Parabolic Louvers**

These are available in small and large designs, the principal characteristic of which is extremely low brightness yielding very high VCP. One such unit with miniature cells is shown in this figure.

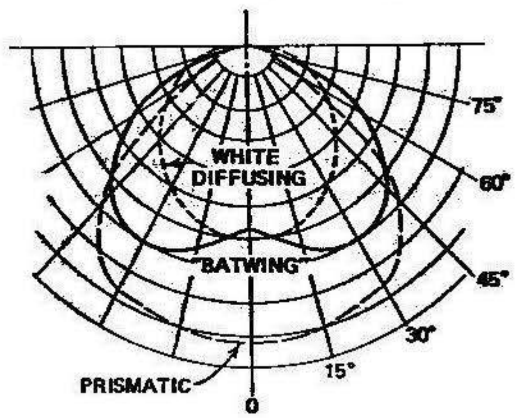
A section through the unit is shown in this figure.

Another design is shown in the figure below along with its distribution curves. Notice the low value of high-angle and low-angle brightness of the crosswise curve. This unit therefore give very high VCP, good ESI, and good efficiency.

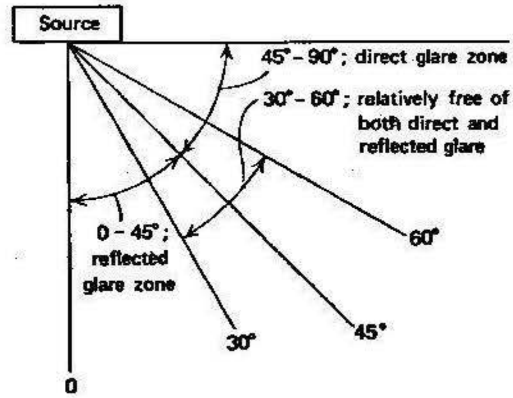


(e) **Batwing Diffusers**

These diffusers are made in a number of designs. They are generally prismatic lenses modified to give this special characteristic.



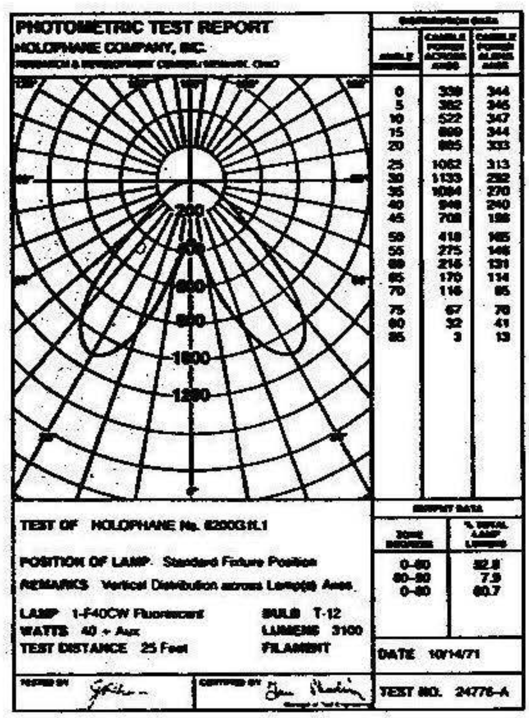
(a)



(a) *Comparison of typical distribution curves for common fluorescent fixture diffuser elements. The white plastic diffuser characteristic is almost circular, giving essentially the same distribution as the bare lamps, since it contains no light control elements. The curve of a typical prismatic diffuser shows high-angle cutoff (low direct glare) but high output in the 0 to 45° reflected glare area. Batwing distribution concentrates output in the 30 to 60° area while reducing the 0 to 30° zone to minimize reflections. All curves are across the axis of a 2 ft x 4 ft recessed fluorescent fixture with four 40-w lamps.*

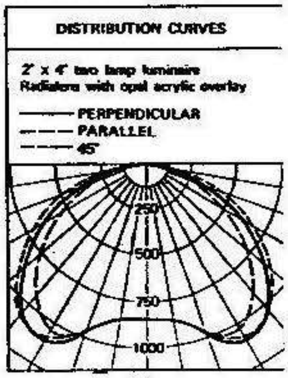
(b) *Linear batwing distribution with extremely sharp cutoff in the upper and lower ranges. Curve taken across lamp axis for Holophane Percepta (registered Trademark) single lamp unit.*

(c) *Complete photometric data for a radial bating distribution lens. Note that the perpendicular, parallel, and diagonal curves are almost identical. Zonal flux is maximum in the 30 to 60° range and drops off at both extremes, as desired.*



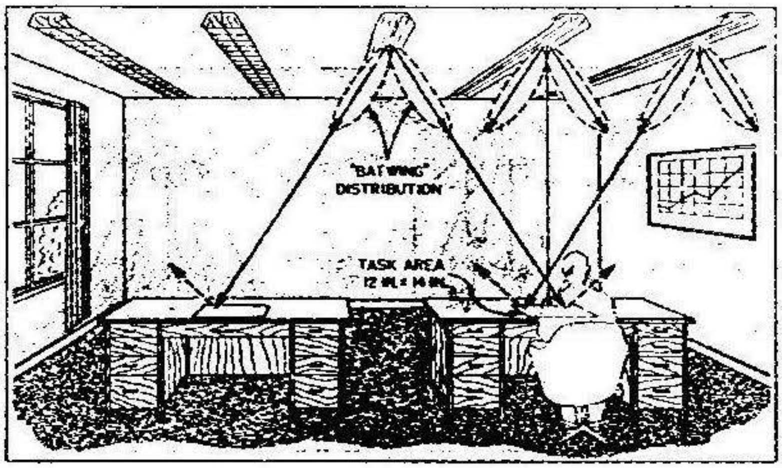
(b)

PHOTOMETRIC DATA:

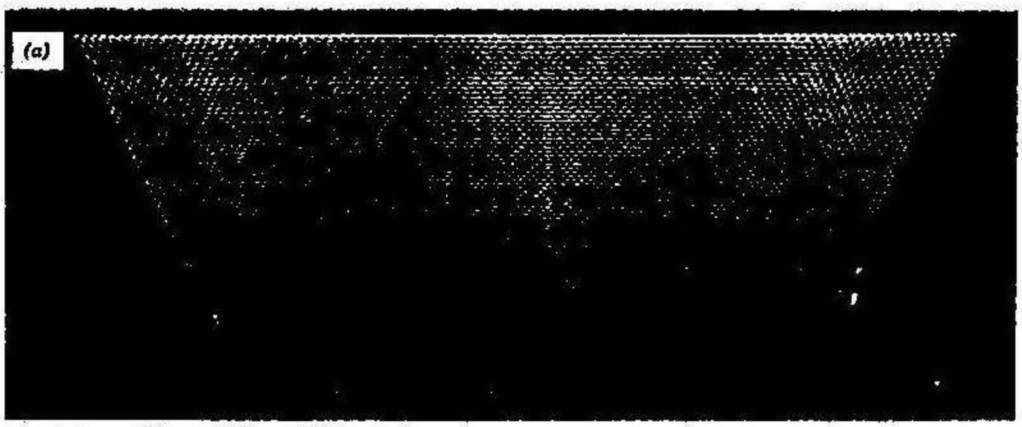


(c)

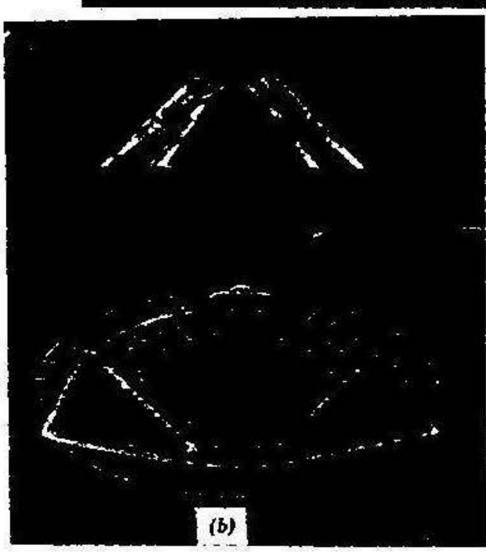
CANDLEPOWER AT 20 FT.				ZONAL FLUX
ANGLE	PERP.	PAR.	45°	
90	0	0	0	–
85	48	38	61	51
75	282	229	288	287
65	553	462	561	526
55	808	687	813	700
45	1013	892	1018	762
35	1152	1045	1130	698
25	1110	1085	1090	505
15	929	929	927	263
5	883	881	883	83
0	880	880	880	–
LUMINAIRE EFFICIENCY – 62.5%				
Brightness values based upon 3100 lumen lamps				



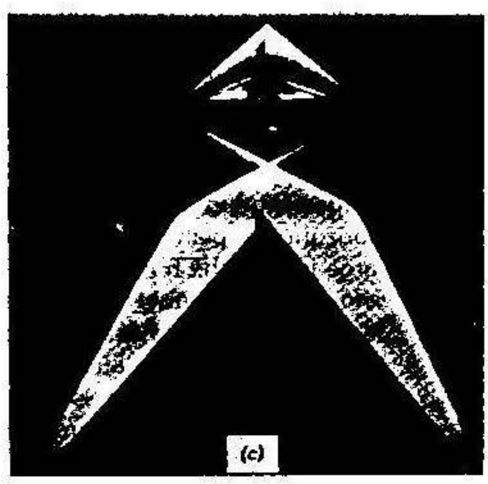
(d)



(a)

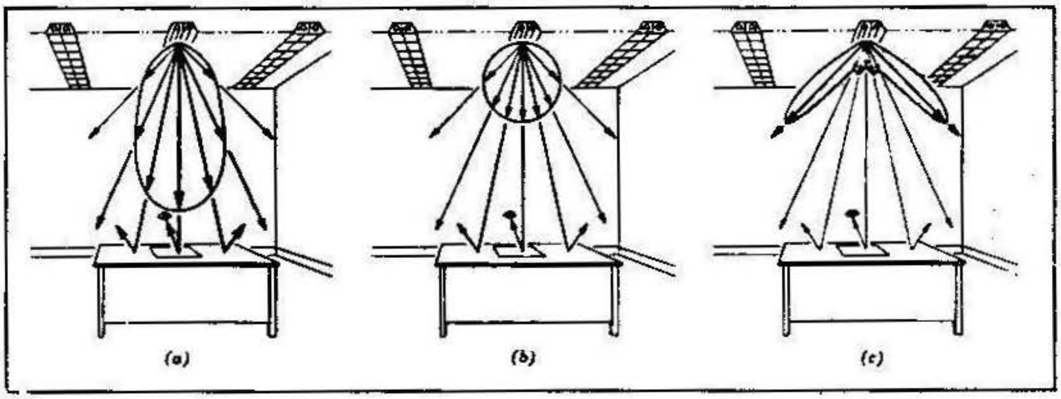


(b)



(c)

A comparison of batwing distribution with that of louvers and white plastic is shown in this figure.



ESI — Equivalent Spherical Illumination
VCP — Visual Comfort Probability

Luminaire Efficiency

A luminaire, variously called a fixture, lighting unit, or reflector, comprises a device for physically supporting the light source and usually for directing or controlling the light output of this source. Because of internal reflections, some of the generated lumen output of the lamp is lost within the fixture. The ratio of output lumens to lamp (input) lumens, expressed as a percentage, represents the luminous efficiency of the fixture. Although this information is normally available from the manufacturer it is readily calculated from the fixture distribution curve by application of the zonal factors to the fixture curve. However, this characteristic has little meaning by itself, since the actual overall efficiency of a luminaire depends on the space in which it is used.

To illustrate, let us consider the case of a large high-ceiling room in which the ceiling is dark and is covered with dirty piping and ductwork. If we were to use a high-efficiency (say 80%) indirect lighting unit in such a room, most of the light directed upward would be lost (absorbed) and the actual lighting on the working plane 30 in. above the floor would be very low. If however, this room were illuminated with low-efficiency direct lighting units (ex: 50%) utilizing the same wattage, the illumination on the working plane would be considerably higher than in the first case.

Similarly, if we consider a small room with dark walls and ceiling, lighted alternatively by diffuse lighting and by direct lighting units of the same wattage and unit efficiency, the horizontal — plane illumination will be higher in the case of the direct units because of the large loss of the horizontal and upward components of the diffuse lighting on the walls and ceiling. It should be obvious than that the fixture efficiency alone is not a meaningful factor but that the overall luminous efficiency of a particular unit in a particular space is the figure that merits our attention. This figure, since it describes the utilization of the fixture output in specific space, is known as the coefficient of utilization (CU). It is defined as the ratio between the lumens reaching the working horizontal plane to the generated lumens.

Since each luminaire will have a different coefficient for every different space in which it is used, a system of standardization has been evolved utilizing room cavities (explained below) of certain proportions and various surface reflectances.

The fixture coefficients are then computed and tabulated as shown in the table. It should be emphasized that the figures given in this table are for the generic fixture type only in an actual job, actual fixture data should be used. The CU then is a factor that combines fixture efficiency and distribution with room proportions, mounting height, and surface reflectance.

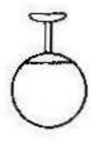
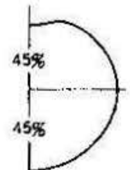
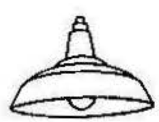
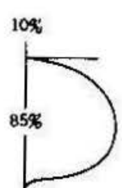
Coefficients of Utilization for Typical Luminaires with Suggested Maximum Spacing Ratios and Maintenance Category

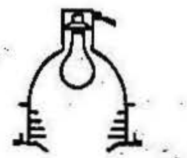
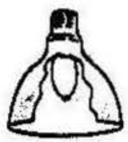
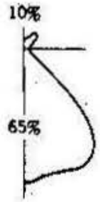
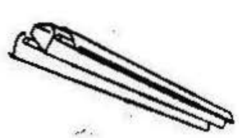
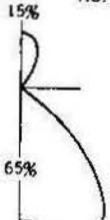
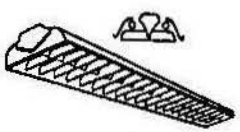
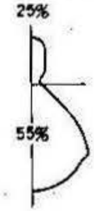
To obtain a Coefficient of Utilization:

1. Determine cavity ratios for the room, ceiling, and floor from Table 20.8.
2. Determine the effective ceiling and floor cavity reflectances from Table 20.9. Use initial ceiling, floor, and wall reflectances.
3. Obtain Coefficient of Utilization (CU) for 20% effective floor cavity reflectance from appropriate table below for luminaire type to be used. Interpolate, when necessary, to obtain CU for exact room cavity ratio for nearest effective ceiling cavity reflectances above and below reflectance obtained in Step 2; interpolate between these CUs to obtain CU for Step 2 ceiling cavity reflectance.
4. If effective floor cavity reflectance differs significantly from 20%, obtain multiplier from Table 20.10 and apply this to the CU obtained in Step 3.

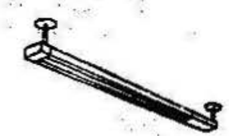
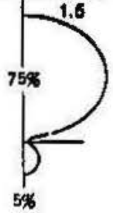
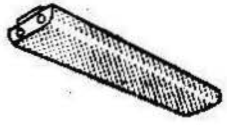
NOTE. In some cases, luminaire data in this table are based on an actual typical luminaire; in other cases, the data represent a composite of generic luminaire types. Therefore, whenever possible, specific luminaire data should be used in preference to this table of typical luminaires.

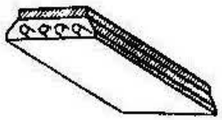
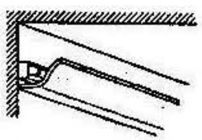
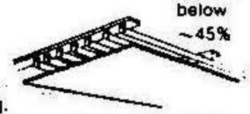
The polar intensity sketch (candlepower distribution curve) and the corresponding spacing-to-mounting height guide are representative of many luminaires of each type shown. A specific luminaire may differ in perpendicular plane (crosswise) and parallel plane (lengthwise) intensity distributions and in S/MH guide from the values shown. However, the various coefficients depend only on the average intensity at each polar angle from nadir.

	Typical Distribution and Percent Lamp Lumens		ρ_{cc}[a] →	80			70			50			30			10			0	
			ρ_w[b] →	50	30	10	50	30	10	50	30	10	50	30	10	50	30	10	0	WDRC[e] ↓
Typical Luminaire	Maint. Cat.	Maximum S/MH Guide[d]	RCR[c] ↓	Coefficients of Utilization for 20% Effective Floor Cavity Reflectance (ρ_{fc} = 20)																
1	V	1.5	0	.87	.87	87	.81	.81	81	.69	.69	69	.59	.59	.59	.49	.49	.49	.44	
			1	.71	.67	.63	.66	.62	.59	.56	.53	.50	.47	.45	43	.39	.37	.35	.31	.35
			2	.61	.54	.49	.56	.50	.46	.47	.43	.39	.39	.36	.33	.32	.29	.27	.23	.27
			3	.52	.45	.39	.48	.42	.37	.41	.36	.31	.34	.30	.26	.27	.24	.22	.18	.22
			4	.46	.38	.33	.42	.36	30	.36	.30	.26	.30	.26	.22	.24	.21	.18	.15	.19
			5	.40	.33	.27	.37	.30	.25	.32	.26	.22	.26	.22	.19	.21	.18	.15	.12	.16
			6	.36	.28	.23	.33	.26	.21	.28	.23	.19	.23	.19	.16	.19	.15	.13	.10	.14
			7	.32	.25	.20	.29	.23	.18	.25	.20	.16	.21	.16	.13	.17	.13	.11	.09	.13
			8	.29	.22	.17	.27	.20	16	.23	.17	.14	.19	.15	12	.15	.12	.09	.07	.12
Pendant diffusing sphere with			9	.26	.19	.15	.24	.18	14	.20	.15	.12	.17	.13	.10	.14	.11	.08	.06	.11
incandescent lamp			10	.23	.17	.13	.22	.16	.12	.19	.14	.10	.16	.12	.09	.13	.09	.07	.05	.10
3	IV	1.3	0	.99	.99	.99	.97	.97	.97	.92	.92	.92	.88	.88	.88	.85	.85	.85	.83	
			1	.88	.85	.82	.86	.83	.81	.83	.80	.78	.79	.78	.76	.77	.75	.73	.72	.29
			2	.78	.73	.68	.76	.72	.67	.73	.69	.66	.71	.67	.64	.68	.65	.63	.61	.28
			3	.69	.62	.57	.67	.61	.57	.65	.60	.56	.63	.58	.55	.61	.57	.54	.52	.26
			4	.61	.54	.49	.60	.53	.48	.58	.52	.48	.56	.51	.47	.54	.50	.46	.45	.24
			5	.54	.47	.41	.53	.46	.41	.51	.45	.41	.50	.44	.40	.48	.43	.40	.38	.23
			6	.48	.41	.35	.47	.40	.35	.46	.39	.35	.44	.39	.34	.43	.38	.34	.32	.21
			7	.43	.35	.30	.42	.35	.30	.41	.34	.30	.39	.34	.30	.38	.33	.29	.28	.20
Porcelain-enameled ventilated			8	.38	.31	.26	.38	.31	.26	.37	.30	.26	.36	.30	.26	.35	.30	.26	.24	.19
standard dome with incandes-			9	.35	.28	.23	.34	.27	23	.33	.27	.23	.32	.27	.23	.31	.26	.22	.21	.17
cent lamp			10	.31	.25	.20	.31	.24	.20	.30	.24	.20	.29	.24	.20	.29	.23	.20	.18	.16

 Reflector downlight with baffles and inside frosted lamp	IV 0.7 	0	.53	.53	.53	.52	.52	.52	.49	.49	.49	.47	.47	.47	.45	.45	.45	.44	
		1	.51	.50	.49	.50	.49	.48	.48	.47	.47	.46	.46	.45	.46	.44	.44	.43	.04
		2	.48	.47	.46	.48	.46	.45	.46	.45	.44	.45	.44	.44	.44	.43	.43	.42	.03
		3	.47	.45	.44	.46	.45	.43	.45	.44	.43	.44	.43	.42	.43	.42	.41	.41	.03
		4	.45	.43	.42	.44	.43	.42	.43	.42	.41	.43	.41	.41	.42	.41	.40	.40	.03
		5	.43	.41	.40	.43	.41	.40	.42	.40	.39	.41	.40	.39	.41	.40	.39	.38	.03
		6	.42	.40	.39	.41	.40	.38	.41	.39	.38	.40	.39	.38	.40	.39	.38	.37	.03
		7	.40	.38	.37	.40	.38	.37	.39	.38	.37	.39	.38	.37	.38	.37	.36	.36	.03
		8	.39	.37	.36	.38	.37	.36	.38	.37	.36	.38	.36	.35	.37	.36	.35	.35	.03
		9	.37	.36	.34	.37	.35	.34	.37	.35	.34	.36	.35	.34	.36	.35	.34	.33	.03
		10	.36	.34	.33	.36	.34	.33	.36	.34	.33	.35	.34	.33	.35	.34	.33	.32	.03
 Wide-distribution ventilated reflector with clear HID lamp	III 1.5 	0	.92	.92	.92	.90	.90	.90	.86	.86	.86	.82	.82	.82	.79	.79	.79	.77	
		1	.85	.82	.80	.83	.81	.79	.79	.78	.76	.76	.75	.74	.74	.72	.71	.70	.19
		2	.77	.73	.70	.75	.72	.69	.73	.70	.67	.70	.68	.66	.68	.66	.64	.63	.19
		3	.70	.65	.61	.68	.64	.60	.66	.62	.59	.64	.61	.58	.62	.59	.57	.56	.18
		4	.63	.58	.53	.62	.57	.53	.60	.56	.52	.58	.55	.52	.57	.54	.51	.49	.18
		5	.57	.51	.47	.56	.51	.47	.55	.50	.46	.53	.49	.46	.52	.48	.45	.44	.17
		6	.51	.45	.41	.51	.45	.41	.49	.44	.40	.48	.43	.40	.47	.43	.40	.38	.16
		7	.46	.40	.36	.45	.39	.35	.44	.39	.36	.43	.38	.35	.42	.38	.34	.33	.16
		8	.41	.35	.31	.41	.35	.31	.40	.34	.31	.39	.34	.30	.38	.33	.30	.29	.15
		9	.37	.31	.27	.37	.31	.27	.36	.30	.27	.35	.30	.27	.34	.30	.26	.26	.15
		10	.33	.27	.24	.33	.27	.23	.32	.27	.23	.31	.27	.23	.31	.26	.23	.22	.14
 Diffuse aluminum reflector with 35°CW shielding	II 1.5/1.3 	0	.94	.94	.94	.90	.90	.90	.82	.82	.82	.75	.75	.75	.69	.69	.69	.66	
		1	.85	.82	.80	.82	.79	.77	.75	.73	.72	.69	.68	.66	.64	.63	.62	.59	.18
		2	.76	.72	.68	.74	.70	.66	.68	.65	.62	.63	.61	.58	.58	.56	.55	.52	.17
		3	.69	.63	.59	.66	.61	.57	.62	.58	.54	.57	.54	.51	.53	.51	.48	.46	.17
		4	.62	.56	.51	.60	.54	.50	.56	.51	.47	.52	.48	.45	.48	.45	.43	.41	.16
		5	.55	.49	.44	.53	.48	.43	.50	.45	.41	.47	.43	.39	.44	.40	.36	.36	.16
		6	.50	.43	.39	.46	.42	.38	.45	.40	.36	.42	.38	.35	.40	.36	.33	.31	.16
		7	.45	.38	.34	.43	.37	.33	.41	.36	.32	.38	.34	.30	.36	.32	.29	.27	.14
		8	.40	.34	.29	.39	.33	.29	.37	.31	.28	.34	.30	.26	.32	.28	.25	.24	.13
		9	.36	.30	.25	.35	.29	.25	.33	.28	.24	.31	.26	.23	.29	.25	.22	.20	.13
		10	.33	.26	.22	.32	.26	.22	.30	.25	.21	.28	.23	.20	.26	.22	.19	.18	.12
 Diffuse aluminum reflector with 35°CW × 35°LW shielding	II 1.5/1.1 	0	.83	.83	.83	.79	.79	.79	.71	.71	.71	.65	.65	.65	.60	.60	.60	.56	
		1	.75	.72	.70	.72	.69	.66	.65	.64	.62	.60	.59	.56	.55	.54	.53	.50	.15
		2	.67	.63	.60	.65	.61	.58	.59	.57	.54	.55	.53	.51	.50	.49	.47	.46	.14
		3	.61	.56	.52	.58	.54	.51	.54	.50	.48	.50	.47	.45	.46	.44	.42	.40	.14
		4	.55	.49	.45	.53	.48	.44	.49	.45	.42	.45	.42	.40	.42	.39	.37	.36	.13
		5	.49	.44	.40	.47	.42	.39	.44	.40	.37	.41	.38	.35	.38	.35	.33	.31	.12
		6	.45	.39	.35	.43	.38	.34	.40	.36	.33	.37	.34	.31	.35	.32	.30	.28	.12
		7	.40	.35	.31	.39	.34	.30	.36	.32	.29	.34	.30	.27	.32	.29	.26	.25	.11
		8	.36	.31	.27	.35	.30	.26	.33	.28	.26	.31	.27	.24	.29	.25	.23	.21	.11
		9	.33	.27	.23	.32	.26	.23	.29	.25	.22	.28	.24	.21	.26	.22	.20	.19	.10
		10	.30	.24	.21	.29	.24	.20	.27	.22	.19	.26	.21	.19	.23	.20	.18	.16	.10

Coefficients of Utilization for Typical Luminaires with Suggested Maximum Spacing Ratios and Maintenance Category

Typical Luminaire	Maint. Cat.	Maximum S/MH Guide[d]	Typical Distribution and Percent Lamp Lumens	ρ_{cc}[a] → / ρ_w[b] → / RCR[c] ↓	80: 5	80: 30	80: 10	70: 50	70: 30	70: 10	50: 50	50: 30	50: 10	30: 50	30: 30	30: 10	10: 50	10: 30	10: 10	0: 0	WDRC[e] ↓
					Coefficients of Utilization for 20% Effective Floor Cavity Reflectance ($\rho_{fc} = 20$)																
	VI	1.5		0	.77	.77	.77	.67	.67	.67	.49	.49	.49	.33	.33	.33	.18	.18	.18	.11	
				1	.67	.64	.62	.59	.57	.54	.44	.42	.41	.30	.29	.28	.17	.16	.16	.10	.04
				2	.59	.54	.50	.51	.48	.45	.38	.38	.34	.26	.25	.23	.15	.14	.13	.09	.04
				3	.51	.46	.42	.45	.41	.37	.34	.31	.28	.23	.21	.20	.13	.12	.12	.07	.04
				4	.45	.40	.35	.40	.35	.31	.30	.27	.24	.20	.18	.17	.12	.11	.10	.06	.03
				5	.40	.34	.30	.35	.30	.27	.26	.23	.20	.18	.16	.14	.10	.09	.08	.05	.03
				6	.36	.30	.26	.32	.27	.23	.24	.20	.18	.16	.14	.12	.09	.08	.07	.05	.03
				7	.32	.26	.22	.28	.23	.20	.21	.18	.15	.15	.12	.11	.08	.07	.08	.04	.03
				8	.29	.23	.19	.25	.21	.17	.19	.16	.13	.13	.11	.09	.08	.06	.06	.03	.03
Luminous bottom suspended				9	.26	.20	.17	.23	.18	.16	.17	.14	.12	.12	.10	.08	.07	.06	.06	.03	.02
unit with extra-high-output lamp			Max. $S/CH_{wp} = 1.5$	10	.24	.18	.15	.21	.16	.13	.16	.12	.10	.11	.09	.07	.06	.05	.04	.03	.02
	V	1.5/1.2		0	.80	.80	.80	.77	.77	.77	.71	.71	.71	.66	.66	.66	.60	.60	.60	.58	
				1	.71	.69	.66	.69	.66	.64	.64	.62	.60	.59	.58	.56	.55	.54	.53	.50	.20
				2	.64	.59	.56	.61	.58	.54	.57	.54	.51	.53	.51	.49	.49	.48	.46	.44	.18
				3	.57	.52	.48	.55	.50	.47	.51	.48	.45	.48	.45	.42	.45	.42	.40	.38	.17
				4	.51	.46	.41	.49	.44	.40	.46	.42	.39	.43	.40	.37	.41	.38	.35	.34	.16
				5	.46	.40	.36	.44	.39	.35	.41	.37	.34	.39	.35	.32	.37	.33	.31	.29	.15
				6	.41	.35	.31	.40	.35	.31	.38	.33	.30	.35	.31	.28	.33	.30	.27	.26	.14
				7	.37	.31	.27	.36	.31	.27	.34	.29	.26	.32	.28	.25	.30	.27	.24	.23	.13
Two-lamp prismatic wrap-				8	.33	.28	.24	.32	.27	.23	.30	.26	.22	.29	.25	.22	.27	.24	.21	.19	.12
around—multiply by 0.95 for				9	.30	.24	.20	.29	.24	.20	.27	.23	.19	.26	.22	.19	.24	.21	.18	.17	.12
four lamps				10	.27	.22	.18	.26	.21	.18	.25	.20	.17	.23	.19	.16	.22	.18	.16	.15	.11
	IV	1.0		0	.59	.59	.59	.58	.58	.58	.55	.55	.55	.53	.53	.53	.51	.51	.51	.50	
				1	.54	.52	.50	.52	.51	.49	.50	.49	.48	.48	.47	.46	.47	.46	.45	.44	.15
				2	.48	.45	.43	.47	.44	.42	.45	.43	.41	.44	.42	.40	.42	.41	.39	.39	.14
				3	.43	.40	.37	.42	.39	.37	.41	.38	.36	.40	.37	.36	.39	.37	.35	.34	.13
				4	.39	.35	.32	.38	.35	.32	.37	.34	.32	.36	.33	.31	.35	.33	.31	.30	.13
				5	.35	.31	.28	.35	.31	.28	.34	.30	.28	.33	.30	.28	.32	.29	.27	.26	.12
				6	.32	.28	.25	.32	.28	.25	.31	.27	.25	.30	.27	.25	.29	.26	.24	.23	.11
Four-lamp, 2-ft-wide troffer with				7	.29	.25	.22	.29	.25	.22	.28	.25	.22	.27	.24	.22	.27	.24	.22	.21	.10
45° plastic louver—multiply by				8	.26	.22	.20	.26	.22	.20	.25	.22	.20	.25	.22	.19	.24	.21	.19	.18	.10
1.05 for two lamps and 0.95 for				9	.24	.20	.17	.24	.20	.17	.23	.20	.17	.23	.19	.17	.22	.19	.17	.16	.09
six lamps			Max. $S/MH_{wp} = 0.9$	10	.22	.18	.16	.22	.18	.18	.21	.18	.16	.21	.18	.15	.20	.17	.15	.15	.09

 Fluorescent unit with flat prismatic lens, 4-lamp, 2 ft wide—multiply by 1.10 for 2-lamp	V 0% 1.4/1.2  65% Max. S/MH_{wp} = 1.2	0	.73	.73	73	.72	.72	.72	.68	.68	.68	.66	.66	.66	.63	.63	.63	.62	
		1	.66	.64	62	.65	.63	.61	.62	.60	.59	.60	.58	.57	.57	.56	.55	.54	.20
		2	.59	.55	.52	.58	.54	.52	.56	.53	.50	.54	.51	.49	.52	.50	.48	.47	.19
		3	.53	.48	.45	.52	.48	.44	.50	.46	.44	.48	.45	.43	.47	.44	.42	.41	.18
		4	.47	.42	.39	.46	.42	.38	.45	.41	.38	.43	.40	.37	.42	.39	.37	.36	.17
		5	.42	.37	.33	.41	.37	.33	.40	.36	.33	.39	.35	.32	.38	.35	.32	.31	.16
		6	.38	.33	.29	.37	.32	.29	.36	.32	.29	.35	.31	.28	.34	.31	.28	.27	.15
		7	.34	.29	.25	.33	.29	.25	33	.28	.25	.32	.28	.26	.31	.27	.25	.23	.14
		8	.30	.25	.22	.30	.25	.22	.29	.25	.22	.28	.24	.21	.26	.24	.21	.20	.13
		9	.27	.22	.19	.27	.22	.19	.26	.22	.19	.25	.21	.19	.25	.21	.18	.17	.12
		10	.25	.20	.17	.24	.20	.16	.24	.19	.16	.23	.19	.16	.23	.19	.16	.15	.12
 Single row fluorescent lamp cove without reflector, mult. by 0.93 for two rows and by 0.85 for three rows.		1	.42	.40	.39	.36	.35	.33	.25	.24	.23	Coves are not recommended for lighting areas having low reflectances.							
		2	.37	.34	.32	.32	.29	.27	.22	.20	.19								
		3	.32	.29	.26	.28	.25	.23	.19	.17	.16								
		4	.29	.25	.22	.25	.22	.19	.17	.15	.13								
		5	.25	.21	.18	.22	.19	.16	.15	.13	.11								
		6	.23	.19	.16	.20	.16	.14	.14	.12	.10								
		7	.20	.17	.14	.17	.14	.12	.12	.10	.09								
		8	.18	.15	.12	.16	.13	.10	.11	.09	.08								
		9	.17	.13	.10	.15	.11	.09	.10	.08	.07								
		10	.15	.12	.09	.13	.10	.08	.09	.07	.06								
ρ_{cc} from below ~45%  Louvered ceiling. 1. Ceiling efficiency ~50%; 45° shielding opaque louvers of 80% reflectance. Cavity with minimum obstructions and painted with 80% reflectance paint—use ρ_c = 50.		1							.51	.49	.48				.47	.46	.45		
		2							.46	.44	.42				.43	.42	.40		
		3							.42	.39	.37				.39	.38	.36		
		4							.38	.35	.33				.36	.34	.32		
		5							.35	.32	.29				.33	.31	.29		
		6							.32	.29	.26				.30	.28	.26		
		7							.29	.26	.23				.28	.25	.23		
		8							.27	.23	.21				.26	.23	.21		
		9							.24	.21	.19				.24	.21	.19		
		10							.22	.19	.17				.22	.19	.17		

Source. Selected and reprinted with permission from *ICS Handbook*, 5th ed.

[a] ρ_{cc} = percent effective ceiling cavity reflectance.

[b] ρ_w = percent wall reflectance.

[c] RCR = Room Cavity Ratio.

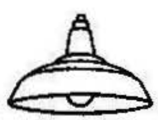
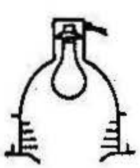
[d] = Maximum *S/MH* guide—ratio of maximum luminaire spacing to mounting or ceiling height above work plane.

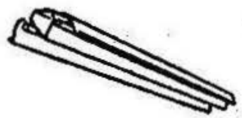
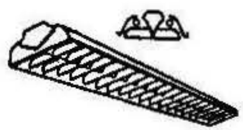
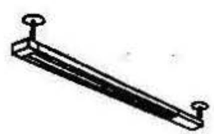
[e] WDRC = Wall Direct Radiation Coefficient.

Wall Luminance Coefficients and Ceiling Cavity Luminance Coefficients for Typical Luminaires

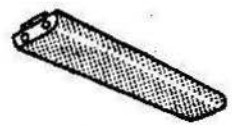
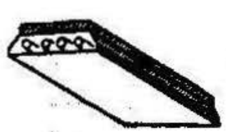
To obtain a luminance coefficient follow the procedure detailed at the head of Table 20.7a to find a coefficient of utilization.

Although it is recommended that luminance coefficients and wall direct radiation coefficients be published to three decimal places, only two are shown here for these typical luminaires. Three decimal place data should be obtained from manufacturers of actual luminaires used.

	ρ_{cc} →	80	70	50	30	10	ρ_{cc} →	80	70	50	30	10
	ρ_w →	50 30 10	50 30 10	50 30 10	50 30 10	50 30 10	ρ_w →	50 30 10	50 30 10	50 30 10	50 30 10	50 30 10
Typical Luminaire	RCR ↓	*Wall luminance coefficients for 20% effective floor cavity reflectance (ρ_{fc} = 20)*					RCR ↓	*Ceiling cavity luminance coefficients for 20% effective floor cavity reflectance (ρ_{fc} = 20)*				
							0	.42 .42 .42	.36 .36 .36	.25 .25 .25	.14 .14 .14	.05 .05 .05
	1	.32 .18 .06	.30 .17 .05	.27 .15 .05	.24 .14 .04	.21 .12 .04	1	.42 .40 .37	.36 .34 .32	.25 .23 .22	.14 .14 .13	.05 .04 .04
	2	.27 .15 .05	.25 .14 .04	.23 .13 .04	.20 .11 .04	.18 .10 .03	2	.42 .38 .35	.36 .33 .30	.24 .23 .21	.14 .13 .12	.05 .04 .04
	3	.24 .13 .04	.22 .12 .04	.20 .11 .03	.17 .09 .03	.15 .08 .03	3	.41 .37 .33	.35 .32 .29	.24 .22 .20	.14 .13 .12	.04 .04 .04
	4	.21 .11 .03	.20 .10 .03	.17 .09 .03	.15 .08 .02	.13 .07 .02	4	.41 .36 .32	.35 .31 .28	.24 .22 .20	.14 .13 .12	.04 .04 .04
	5	.19 .10 .03	.18 .09 .03	.16 .08 .02	.14 .07 .02	.12 .06 .02	5	.40 .35 .31	.34 .30 .27	.24 .21 .19	.14 .12 .11	.04 .04 .04
	6	.18 .09 .03	.16 .08 .02	.14 .07 .02	.13 .07 .02	.11 .06 .02	6	.39 .34 .31	.34 .30 .27	.23 .21 .19	.14 .12 .11	.04 .04 .04
	7	.16 .08 .02	.15 .08 .02	.13 .07 .02	.12 .06 .02	.10 .05 .02	7	.39 .34 .31	.33 .29 .27	.23 .21 .19	.13 .12 .11	.04 .04 .04
	8	.15 .07 .02	.14 .07 .02	.12 .06 .02	.11 .05 .02	.09 .05 .01	8	.38 .34 .30	.33 .29 .26	.23 .20 .19	.13 .12 .11	.04 .04 .04
	9	.14 .07 .02	.13 .06 .02	.12 .06 .02	.10 .05 .01	.09 .04 .01	9	.38 .33 .30	.33 .29 .26	.23 .20 .19	.13 .12 .11	.04 .04 .04
Pendant diffusing sphere with incandescent lamp	10	.13 .06 .02	.12 .06 .02	.11 .05 .01	.09 .05 .01	.08 .04 .01	10	.37 .33 .30	.32 .29 .26	.22 .20 .19	.13 .12 .11	.04 .04 .04
							0	.15 .15 .15	.13 .13 .13	.09 .09 .09	.05 .05 .05	.02 .02 .02
	1	.23 .13 .04	.23 .13 .04	.21 .12 .04	.20 .12 .04	.20 .11 .04	1	.15 .13 .11	.13 .11 .10	.09 .08 .07	.05 .04 .04	.02 .01 .01
	2	.22 .12 .04	.22 .12 .04	.21 .11 .04	.20 .11 .03	.19 .11 .03	2	.14 .11 .08	.12 .09 .07	.08 .07 .05	.05 .04 .03	.02 .01 .01
	3	.21 .11 .03	.21 .11 .03	.20 .11 .03	.19 .10 .03	.18 .10 .03	3	.13 .10 .06	.12 .08 .06	.08 .06 .04	.05 .03 .02	.01 .01 .01
	4	.20 .10 .03	.19 .10 .03	.19 .10 .03	.18 .10 .03	.17 .09 .03	4	.13 .08 .05	.11 .07 .04	.08 .05 .03	.04 .03 .02	.01 .01 .01
	5	.19 .09 .03	.18 .09 .03	.18 .09 .03	.17 .09 .03	.16 .09 .03	5	.12 .08 .04	.11 .07 .04	.07 .05 .02	.04 .03 .01	.01 .01 .00
	6	.18 .09 .03	.17 .09 .03	.17 .09 .02	.16 .08 .02	.16 .08 .02	6	.12 .07 .03	.10 .06 .03	.07 .04 .02	.04 .02 .01	.01 .01 .00
	7	.17 .08 .02	.16 .08 .02	.16 .08 .02	.15 .08 .02	.15 .08 .02	7	.11 .06 .03	.10 .05 .02	.07 .04 .02	.04 .02 .01	.01 .01 .00
	8	.16 .08 .02	.15 .08 .02	.15 .07 .02	.14 .07 .02	.14 .07 .02	8	.11 .06 .02	.09 .05 .02	.06 .04 .01	.04 .02 .01	.01 .01 .00
Porcelain-enameled ventilated standard dome with incandescent lamp	9	.15 .07 .02	.15 .07 .02	.14 .07 .02	.14 .07 .02	.13 .07 .02	9	.10 .05 .02	.09 .05 .02	.06 .03 .01	.04 .02 .01	.01 .01 .00
	10	.14 .07 .02	.14 .07 .02	.13 .07 .02	.13 .06 .02	.13 .06 .02	10	.10 .05 .02	.09 .04 .02	.06 .03 .01	.03 .02 .01	.01 .01 .00
							0	.08 .08 .08	.07 .07 .07	.04 .04 .04	.03 .03 .03	.01 .01 .01
	1	.06 .03 .01	.06 .03 .01	.05 .03 .01	.06 .03 .01	.04 .02 .01	1	.08 .07 .07	.06 .06 .06	.04 .04 .04	.03 .02 .02	.01 .01 .01
	2	.05 .03 .01	.05 .03 .01	.05 .03 .01	.04 .02 .01	.04 .02 .01	2	.07 .06 .05	.06 .05 .05	.04 .04 .03	.02 .02 .02	.01 .01 .01
	3	.05 .03 .01	.05 .03 .01	.04 .02 .01	.04 .02 .01	.04 .02 .01	3	.06 .05 .04	.05 .04 .04	.04 .03 .03	.02 .02 .02	.01 .01 .01
	4	.05 .02 .01	.05 .02 .01	.04 .02 .01	.04 .02 .01	.04 .02 .01	4	.05 .04 .04	.05 .04 .03	.03 .03 .02	.02 .02 .01	.01 .01 .00
	5	.05 .02 .01	.04 .02 .01	.04 .02 .01	.04 .02 .01	.04 .02 .01	5	.05 .04 .03	.04 .03 .03	.03 .02 .02	.02 .01 .01	.01 .00 .00
	6	.04 .02 .01	.04 .02 .01	.04 .02 .01	.04 .02 .01	.04 .02 .01	6	.05 .03 .03	.04 .03 .02	.03 .02 .02	.02 .01 .01	.01 .00 .00
	7	.04 .02 .01	.04 .02 .01	.04 .02 .01	.04 .02 .01	.03 .02 .01	7	.04 .03 .02	.04 .03 .02	.03 .02 .01	.01 .01 .01	.00 .00 .00
	8	.04 .02 .01	.04 .02 .01	.04 .02 .01	.04 .02 .01	.03 .02 .01	8	.04 .03 .02	.03 .02 .02	.02 .02 .01	.01 .01 .01	.00 .00 .00
	9	.04 .02 .01	.04 .02 .01	.04 .02 .01	.03 .02 .00	.03 .02 .00	9	.04 .02 .02	.03 .02 .01	.02 .02 .01	.01 .01 .01	.00 .00 .00
Reflector downlight with baffles and inside frosted lamp.	10	.04 .02 .00	.04 .02 .00	.04 .02 .00	.03 .02 .00	.03 .02 .00	10	.04 .02 .01	.03 .02 .01	.02 .01 .01	.01 .01 .01	.00 .00 .00

								0	.15 .15 .15	.13 .13 .13	.08 .08 .08	.05 .05 .05	.02 .02 .02
	1	.18 .10 .03	.17 .10 .03	.16 .09 .03	.15 .09 .03	.14 .08 .03	1	.14 .13 .11	.12 .11 .10	.08 .08 .07	.05 .04 .04	.02 .01 .01
	2	.17 .09 .03	.16 .09 .03	.15 .09 .03	.15 .08 .03	.14 .08 .02	2	.13 .11 .09	.11 .09 .08	.08 .06 .05	.04 .03 .03	.01 .01 .01
	3	.16 .09 .03	.16 .08 .03	.15 .08 .02	.14 .08 .02	.14 .08 .02	3	.12 .09 .07	.11 .08 .06	.07 .06 .04	.04 .03 .03	.01 .01 .01
	4	.16 .08 .02	.16 .08 .02	.14 .08 .02	.14 .07 .02	.13 .07 .02	4	.12 .08 .06	.10 .07 .05	.07 .05 .03	.04 .04 .02	.01 .01 .01
	5	.15 .08 .02	.15 .07 .02	.14 .07 .02	.13 .07 .02	.13 .07 .02	5	.11 .07 .05	.10 .06 .04	.07 .04 .03	.04 .03 .02	.01 .01 .01
	6	.14 .07 .02	.14 .07 .02	.14 .07 .02	.13 .07 .02	.13 .07 .02	6	.11 .07 .04	.09 .06 .03	.06 .04 .02	.04 .02 .01	.01 .01 .00
	7	.14 .07 .02	.14 .07 .02	.13 .07 .02	.13 .07 .02	.12 .06 .02	7	.10 .06 .03	.09 .05 .03	.06 .04 .02	.04 .02 .01	.01 .01 .00
	8	.13 .07 .02	.13 .06 .02	.13 .06 .02	.12 .06 .02	.12 .06 .02	8	.10 .06 .03	.09 .05 .03	.06 .04 .02	.03 .02 .01	.01 .01 .00
Wide-distribution ventilated reflector with clear HID lamp	9	.13 .06 .02	.13 .06 .02	.12 .06 .02	.12 .06 .02	.11 .06 .02	9	.10 .05 .03	.08 .05 .02	.06 .03 .02	.03 .02 .01	.01 .01 .00
	10	.12 .06 .02	.12 .06 .02	.12 .06 .02	.11 .06 .02	.11 .06 .02	10	.09 .05 .02	.08 .04 .02	.06 .03 .01	.03 .02 .01	.01 .01 .00
								0	.28 .28 .28	.24 .24 .24	.16 .16 .16	.09 .09 .09	.03 .03 .03
	1	.20 .11 .04	.19 .11 .03	.17 .10 .03	.15 .09 .03	.13 .08 .02	1	.27 .26 .24	.23 .22 .21	.16 .16 .15	.09 .09 .08	.03 .03 .03
	2	.19 .10 .03	.18 .10 .03	.16 .09 .03	.15 .08 .03	.13 .07 .02	2	.27 .24 .22	.23 .21 .19	.16 .14 .13	.09 .08 .08	.03 .03 .03
	3	.18 .10 .03	.17 .09 .03	.15 .08 .03	.14 .08 .02	.13 .07 .02	3	.26 .22 .20	.22 .19 .17	.15 .13 .12	.09 .08 .07	.03 .03 .02
	4	.17 .09 .03	.16 .08 .03	.15 .08 .02	.13 .07 .02	.12 .07 .02	4	.25 .21 .18	.22 .18 .16	.15 .13 .11	.09 .08 .07	.03 .02 .02
	5	.16 .08 .02	.16 .08 .02	.14 .07 .02	.13 .07 .02	.12 .06 .02	5	.25 .21 .17	.21 .18 .15	.15 .12 .11	.08 .07 .06	.03 .02 .02
	6	.15 .08 .02	.15 .07 .02	.14 .07 .02	.12 .06 .02	.11 .06 .02	6	.24 .20 .17	.21 .17 .15	.14 .12 .10	.08 .07 .06	.03 .02 .02
	7	.15 .07 .02	.14 .07 .02	.13 .07 .02	.12 .06 .02	.11 .06 .02	7	.24 .19 .16	.20 .17 .14	.14 .12 .10	.08 .07 .06	.03 .02 .02
	8	.14 .07 .02	.13 .07 .02	.12 .06 .02	.11 .06 .02	.11 .05 .02	8	.23 .19 .16	.20 .16 .14	.14 .11 .10	.08 .07 .06	.03 .02 .02
Diffuse aluminum reflector with 35° crosswise shielding	9	.13 .06 .02	.13 .06 .02	.12 .06 .02	.11 .06 .02	.10 .05 .01	9	.23 .19 .15	.20 .16 .13	.14 .11 .10	.08 .07 .06	.03 .02 .02
	10	.13 .06 .02	.12 .06 .02	.11 .06 .02	.11 .05 .01	.10 .05 .01	10	.23 .16 .15	.20 .16 .13	.14 .11 .09	.08 .07 .06	.03 .02 .02
								0	.26 .26 .26	.22 .22 .22	.15 .15 .15	.09 .09 .09	.03 .03 .03
	1	.17 .10 .03	.16 .09 .03	.14 .08 .05	.13 .07 .02	.11 .06 .02	1	.26 .24 .23	.22 .21 .20	.16 .14 .14	.09 .08 .08	.03 .03 .03
	2	.16 .09 .03	.15 .09 .03	.14 .08 .02	.12 .07 .02	.11 .06 .02	2	.26 .23 .21	.21 .20 .18	.16 .14 .13	.08 .08 .07	.03 .03 .02
	3	.15 .08 .02	.15 .06 .02	.13 .07 .02	.12 .06 .02	.10 .06 .02	3	.24 .21 .19	.21 .19 .17	.14 .13 .12	.08 .08 .07	.03 .02 .02
	4	.15 .06 .02	.14 .07 .02	.13 .07 .02	.11 .06 .02	.10 .06 .02	4	.24 .21 .19	.20 .18 .16	.14 .12 .11	.08 .07 .07	.03 .02 .02
	5	.14 .07 .02	.13 .07 .02	.12 .06 .02	.11 .06 .02	.10 .06 .02	5	.23 .20 .17	.20 .17 .15	.14 .12 .11	.08 .07 .06	.03 .02 .02
	6	.13 .07 .02	.13 .06 .02	.11 .06 .02	.10 .06 .02	.09 .05 .01	6	.23 .18 .17	.20 .17 .14	.14 .12 .10	.08 .07 .06	.03 .02 .02
	7	.13 .06 .02	.12 .06 .02	.11 .06 .02	.10 .05 .01	.08 .06 .01	7	.23 .19 .18	.19 .16 .14	.13 .11 .10	.08 .07 .06	.03 .02 .02
	8	.12 .06 .02	.12 .06 .02	.11 .06 .02	.10 .05 .01	.08 .04 .01	8	.23 .18 .16	.19 .16 .14	.13 .11 .10	.08 .07 .06	.02 .02 .02
Diffuse aluminum reflector with 35° crosswise and 35° lengthwise shielding	9	.12 .06 .02	.11 .05 .02	.10 .06 .01	.09 .05 .01	.08 .04 .01	9	.22 .18 .16	.19 .16 .13	.13 .11 .10	.08 .08 .06	.02 .02 .02
	10	.11 .05 .01	.11 .05 .01	.10 .06 .01	.09 .04 .01	.08 .04 .01	10	.22 .18 .16	.19 .16 .13	.13 .11 .08	.08 .06 .06	.02 .02 .02
								0	.66 .66 .66	.55 .55 .55	.38 .38 .38	.22 .22 .22	.07 .07 .07
	1	.20 .12 .04	.18 .10 .03	.13 .08 .02	.08 .05 .02	.05 .03 .01	1	.65 .63 .62	.55 .54 .53	.38 .37 .37	.22 .22 .21	.07 .07 .07
	2	.19 .10 .03	.17 .09 .03	.12 .07 .02	.08 .05 .01	.04 .03 .01	2	.64 .61 .59	.55 .53 .51	.38 .37 .36	.22 .21 .21	.07 .07 .07
	3	.17 .09 .03	.15 .08 .02	.11 .06 .02	.08 .04 .01	.04 .02 .01	3	.64 .60 .58	.55 .52 .50	.37 .36 .35	.22 .21 .21	.07 .07 .07
	4	.16 .08 .02	.14 .07 .02	.11 .06 .02	.07 .04 .01	.04 .02 .01	4	.63 .59 .57	.54 .51 .49	.37 .36 .35	.22 .21 .21	.07 .07 .07
	5	.15 .08 .02	.13 .07 .02	.10 .05 .02	.07 .04 .01	.04 .02 .01	5	.63 .59 .56	.54 .51 .49	.37 .36 .34	.21 .21 .20	.07 .07 .07
	6	.14 .07 .02	.12 .06 .02	.09 .05 .01	.06 .03 .01	.03 .02 .01	6	.06 .58 .55	.54 .50 .48	.37 .35 .34	.21 .21 .20	.07 .07 .07
	7	.13 .07 .02	.12 .06 .02	.09 .04 .01	.06 .03 .01	.03 .02 .01	7	.62 .58 .55	.53 .50 .48	.37 .35 .34	.21 .21 .20	.07 .07 .07
	8	.12 .06 .02	.11 .05 .02	.08 .04 .01	.06 .03 .01	.03 .02 .00	8	.61 .57 .56	.53 .50 .48	.37 .35 .34	.21 .21 .20	.07 .07 .07
Luminous bottom suspended unit with extra-high-output lamp	9	.12 .06 .02	.10 .05 .01	.08 .04 .01	.06 .03 .01	.03 .02 .00	9	.61 .57 .55	.53 .50 .48	.36 .35 .34	.21 .21 .20	.07 .07 .07
	10	.11 .05 .01	.10 .05 .01	.07 .04 .01	.05 .02 .01	.03 .01 .00	10	.61 .57 .54	.52 .49 .47	.36 .36 .34	.21 .21 .20	.07 .07 .07

Wall Luminance Coefficients and Ceiling Cavity Luminance Coefficients for Typical Luminaires (Continued)

	ρ_{cc} →	80			70			50			30			10			ρ_{cc} →	80			70			50			30			10		
	ρ_w →	50	30	10	50	30	10	50	30	10	50	30	10	50	30	10	ρ_w →	50	30	10	50	30	10	50	30	10	50	30	10	50	30	10
Typical Luminaire	RCR ↓	Wall luminance coefficients for 20% effective floor cavity reflectance (ρ_{fc} = 20)															RCR ↓	Ceiling cavity luminance coefficients for 20% effective floor cavity reflectance (ρ_{fc} = 20)														
 Two-lamp prismatic wraparound—multiply by 0.95 for 4 lamps																	0	.22	.22	.22	.18	.18	.18	.12	.12	.12	.07	.07	.07	.02	.02	.02
	1	.19	.11	.03	.18	.10	.03	.17	.10	.03	.15	.09	.03	.14	.08	.03	1	.21	.20	.18	.18	.17	.16	.12	.12	.11	.07	.07	.06	.02	.02	.02
	2	.18	.10	.03	.17	.09	.03	.15	.09	.03	.14	.08	.02	.13	.07	.02	2	.21	.18	.16	.18	.16	.14	.12	.11	.10	.07	.06	.06	.02	.02	.02
	3	.16	.09	.03	.16	.08	.03	.14	.08	.02	.13	.07	.02	.12	.07	.02	3	.20	.17	.14	.17	.16	.13	.12	.10	.09	.07	.06	.05	.02	.02	.02
	4	.15	.08	.02	.15	.08	.02	.14	.07	.02	.12	.07	.02	.12	.06	.02	4	.19	.16	.13	.17	.14	.12	.11	.10	.08	.07	.06	.05	.02	.02	.02
	5	.14	.07	.02	.14	.07	.02	.13	.07	.02	.12	.06	.02	.11	.06	.02	5	.19	.15	.13	.16	.13	.11	.11	.09	.08	.06	.06	.05	.02	.02	.02
	6	.14	.07	.02	.13	.07	.02	.12	.06	.02	.11	.06	.02	.10	.05	.02	6	.18	.15	.12	.16	.13	.10	.11	.09	.07	.06	.06	.04	.02	.02	.01
	7	.13	.06	.02	.12	.06	.02	.12	.06	.02	.11	.05	.02	.10	.05	.02	7	.18	.14	.11	.16	.12	10	.11	.09	.07	.06	.06	.04	.02	.02	.01
	8	.12	.06	.02	.12	.06	.02	.11	.06	.02	.10	.05	.01	.10	.05	.01	8	.18	.14	.11	.15	.12	10	.11	.08	.07	.06	.06	.04	.02	.02	.01
	9	.12	.06	.02	.11	.05	.02	.11	.06	.01	.10	.05	.01	.09	.05	.01	9	.17	.13	.11	.15	.12	.09	.10	.08	.07	.06	.05	.04	.02	.02	.01
	10	.11	.05	.01	.11	.05	.01	.10	.05	.01	.09	.06	.01	.09	.04	.01	10	.17	.13	.11	.15	.11	.09	.10	.08	.07	.06	.06	.04	.02	.02	.01
 Four-lamp, 2-ft-wide troffer with 45° plastic louver—multiply by 1.06 for 2 lamps and 0.95 for 6 lamps.																	0	.09	.09	.09	.08	.08	.08	.05	.06	.05	.03	.03	.03	.01	.01	.01
	1	.13	.07	.02	.12	.07	.02	.12	.07	.02	.11	.06	.02	.10	.06	.02	1	.09	.08	.07	.08	.07	.06	.05	.05	.04	.03	.03	.02	.01	.01	.01
	2	.12	.07	.02	.12	.06	.02	.11	.06	.02	.11	.06	.02	.10	.06	.02	2	.08	.07	.05	.07	.06	.05	.05	.04	.03	.03	.02	.02	.01	.01	.01
	3	.11	.06	.02	.11	.06	.02	.11	.06	.02	.10	.06	.02	.10	.05	.02	3	.08	.06	.04	.07	.05	.03	.05	.03	.02	.03	.02	.01	.01	.01	.00
	4	.11	.06	.02	.10	.05	.02	.10	.06	.02	.10	.05	.02	.09	.06	.02	4	.07	.05	.03	.06	.04	.03	.04	.03	.02	.03	.02	.01	.01	.01	.00
	5	.10	.05	.01	.10	.05	.01	.10	.05	.01	.09	.05	.01	.09	.05	.01	5	.07	.04	.03	.06	.04	.02	.04	.03	.02	.02	.02	.01	.01	.01	.00
	6	.10	.05	.01	.09	.05	.01	.09	.05	.01	.09	.04	.01	.08	.04	.01	6	.07	.04	.02	.06	.04	.02	.04	.02	.01	.02	.01	.01	.01	.00	.00
	7	.09	.04	.01	.09	.04	.01	.09	.04	.01	.08	.04	.01	.08	.04	.01	7	.06	.04	.02	.06	.03	.02	.04	.02	.01	.02	.01	.01	.01	.00	.00
	8	.09	.04	.01	.08	.04	.01	.08	.04	.01	.08	.04	.01	.08	.04	.01	8	.06	.03	.02	.05	.03	.01	.04	.02	.01	.02	.01	.01	.01	.00	.00
	9	.08	.04	.01	.08	.04	.01	.08	.04	.01	.08	.04	.01	.07	.04	.01	9	.06	.03	.01	.05	.03	.01	.04	.02	.01	.02	.01	.00	.01	.00	.00
	10	.08	.04	.01	.08	.04	.01	.07	.04	.01	.07	.04	.01	.07	.04	.01	10	.06	.03	.01	.05	.03	.01	.03	.02	.01	.02	.01	.00	.01	.00	.00
 Fluorescent unit with flat prismatic lens; four-lamp, 2 ft wide—multiply by 1.10 for 2 lamps.																	0	.11	.11	.11	.10	.10	.10	.06	.06	.06	.04	.04	.04	.01	.01	.01
	1	.16	.09	.03	.16	.09	.03	.15	.09	.03	.14	.08	.03	.14	.08	.03	1	.11	.10	.09	.09	.08	.07	.06	.06	.05	.04	.03	.03	.01	.01	.01
	2	.15	.08	.03	.15	.08	.03	.14	.08	.02	.14	.08	.02	.13	.07	.02	2	.10	.08	.06	.09	.07	.06	.06	.05	.04	.03	.03	.02	.01	.01	.01
	3	.15	.08	.02	.14	.08	.02	.14	.07	.02	.13	.07	.02	.13	.07	.02	3	.10	.07	.05	.08	.06	.04	.06	.04	.03	.03	.02	.02	.01	.01	.01
	4	.14	.07	.02	.13	.07	.02	.13	.07	.02	.12	.07	.02	.12	.06	.02	4	.09	.06	.04	.08	.05	.03	.05	.04	.02	.03	.02	.01	.01	.01	.00
	5	.13	.07	.02	.13	.07	.02	.12	.06	.02	.12	.06	.02	.11	.06	.02	5	.09	.06	.03	.08	.05	.03	.05	.03	.02	.03	.02	.01	.01	.01	.00
	6	.12	.06	.02	.12	.06	.02	.12	.06	.02	.11	.06	.02	.11	.06	.02	6	.09	.05	.03	.07	.04	.02	.05	.03	.02	.03	.02	.01	.01	.01	.00
	7	.12	.06	.02	.12	.06	.02	.11	.06	.02	.11	.06	.02	.10	.05	.02	7	.08	.05	.02	.07	.04	.02	.05	.03	.01	.03	.02	.01	.01	.01	.00
	8	.11	.06	.02	.11	.06	.02	.11	.05	.02	.10	.05	.02	.10	.05	.01	8	.08	.04	.02	.07	.04	.02	.06	.03	.01	.03	.02	.01	.01	.01	.00
	9	.11	.05	.01	.10	.06	.01	.10	.05	.01	.10	.05	.01	.10	.05	.01	9	.08	.04	.02	.07	.03	.01	.05	.02	.01	.03	.01	.01	.01	.00	.00
	10	.10	.05	.01	.10	.05	.01	.10	.05	.01	.09	.05	.01	.09	.05	.01	10	.07	.04	.01	.06	.03	.01	.04	.02	.01	.03	.01	.01	.01	.00	.00

Interior Illumination Calculations

Having selected a luminaire on the basis of all the foregoing criteria, it remains only to calculate the number of such units required in each space for general illumination, and to properly arrange them. Although a number of calculation methods are available, the lumen method is simplest and most applicable to our needs for area lighting calculations. Intensity calculation from point, line, or area sources is covered in the next sections.

Light Loss Factor (LLF) in Lumen Calculations

The lumen method of calculation is a procedure for determining the average maintained footcandle illumination intensity on the working plane in a room. The method presupposes that luminaires will be spaced so that, uniformity of illumination is provided in order that an average calculation have validity. The method is based on the definition of one footcandle as one lumen incident on one square foot of area. Or

$$\text{footcandles (fc)} = \frac{\text{lumens (1m)}}{\text{area in sq. ft.}}$$

The ratio between the lumens reaching the working plane and the lumens generated is the coefficient of utilization, CU. Or

$$\text{lumens on the working plane} = \text{lamp lumens} \times \text{CU}$$

Therefore:

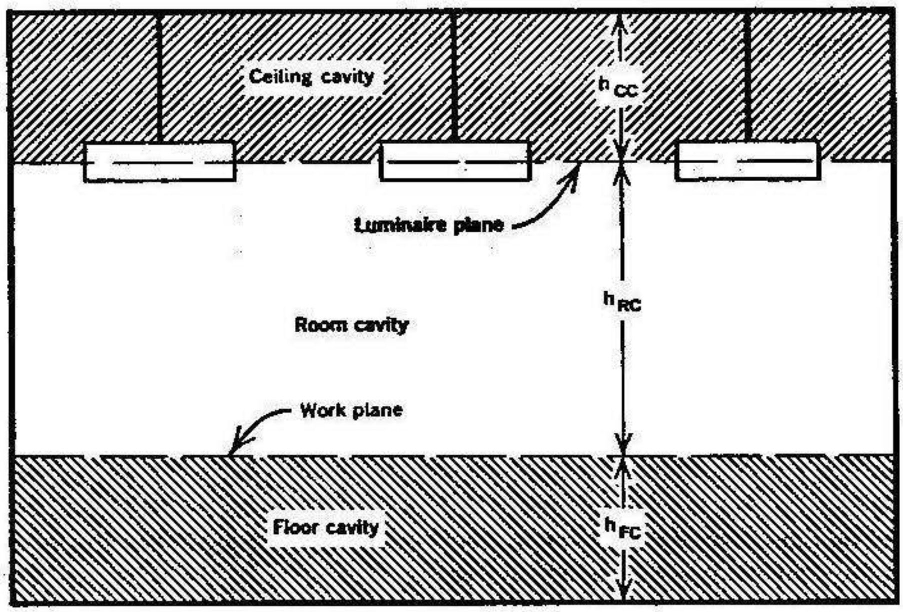
$$\text{fc} = \frac{\text{Lamp lumens} \times \text{CU}}{\text{area}}$$

The footcandle figure so calculated is initial average illumination. This initial level is reduced by the effect of temperature and voltage variations, dirt accumulation on luminaires and room surfaces, lamp output depreciation, and maintenance conditions. All these effects are cumulatively referred to do the light loss factor, LLF:

$$\text{Maintained fc} = \text{initial fc} \times \text{LLF}$$

Zonal Cavity Calculation Method

In the zonal cavity method, the room is divided into three cavities, that is, CEILING, ROOM, and FLOOR, and the "effective" reflectance of each cavity calculated. A detailed explanation of the method plus several illustrative examples will demonstrate its use. Refer to this figure.



Step 1. Refer to the above figure. The room is divided into three cavities; The ceiling cavity is the space between the fixture and the ceiling, the floorcavity space between the floor and the work plane, and the room cavity the space in between that is, between the work plane and the luminaire center line. In offices, schools, and many other occupancies the work plane is 30 in. (0.75 M) In drafting rooms it is 36 to 38 in. (91 to 96.5 cm), in shops 42 to 48 in. (106 to 121.5 cm), in carpet and sail-cutting rooms the work plane is at the floor level. The 3 "h" terms are the heights of the various cavities. In this step also identify the maintained reflectance of the room surfaces and fill in the sketch of the above figure, CC, RC, FC. If the initial surface reflectance of the ceiling is 90% and a 10% deterioration is expected, use 80% for the ceiling reflection. Similarly, establish wall and floor reflectances by specification or by assumption. Utilize the nearest reflectance given in this table.

Percent Effective Ceiling or Floor Cavity Reflectance for Various Reflectance Combinations

Percent Ceiling or Floor Reflectance	90				80				70			50			30				10		
Percent Wall Reflectance	90	70	50	30	80	70	50	30	70	50	30	70	50	30	65	50	30	10	50	30	10
Ceiling or Floor Cavity Ratio																					
0	90	90	90	90	80	80	80	80	70	70	70	50	50	50	30	30	30	30	10	10	10
0.1	90	89	88	87	79	79	78	78	69	69	68	59	49	48	30	30	29	29	10	10	10
0.2	89	88	86	85	79	78	77	76	68	67	66	49	48	47	30	29	29	28	10	10	9
0.3	89	87	85	83	78	77	75	74	68	66	64	49	47	46	30	29	28	27	10	10	9
0.4	88	86	83	81	78	76	74	72	67	65	63	48	46	45	30	29	27	26	11	10	9
0.5	88	85	81	78	77	75	73	70	66	64	61	48	46	44	29	28	27	25	11	10	9
0.6	88	84	80	76	77	75	71	68	65	62	59	47	45	43	29	28	26	25	11	10	9
0.7	88	83	78	74	76	74	70	66	65	61	58	47	44	42	29	28	26	24	11	10	8
0.8	87	82	77	73	75	73	69	65	64	60	56	47	43	41	29	27	25	23	11	10	8
0.9	87	81	76	71	75	72	68	63	63	59	55	46	43	40	29	27	25	22	11	9	8
1.0	86	80	74	69	74	71	66	61	63	58	53	46	42	39	29	27	24	22	11	9	8
1.1	86	79	73	67	74	71	65	60	62	57	52	46	41	38	29	26	24	21	11	9	8
1.2	86	78	72	65	73	70	64	58	61	56	50	45	41	37	29	26	23	20	12	9	7
1.3	85	78	70	64	73	69	63	57	61	55	49	45	40	36	29	26	23	20	12	9	7
1.4	85	77	69	62	72	68	62	55	60	54	48	45	40	35	28	26	22	19	12	9	7
1.5	85	76	68	61	72	68	61	54	59	53	47	44	39	34	28	25	22	18	12	9	7
1.6	85	75	66	59	71	67	60	53	59	52	45	44	39	33	28	25	21	18	12	9	7
1.7	84	74	65	58	71	66	59	52	58	51	44	44	38	32	28	25	21	17	12	9	7
1.8	84	73	64	56	70	65	58	50	57	50	43	43	37	32	28	25	21	17	12	9	6
1.9	84	73	63	55	70	65	57	49	57	49	42	43	37	31	28	25	20	16	12	9	6
2.0	83	72	62	53	69	64	56	48	56	48	41	43	37	30	28	24	20	16	12	9	6

Ceiling or Floor Cavity Ratio

2.1	83	71	61	52	69	63	55	47	56	47	40	43	36	29	28	24	20	16	13	9	6
2.2	83	70	60	51	68	63	54	45	55	46	39	42	36	29	28	24	19	15	13	9	6
2.3	83	69	59	50	68	62	53	44	54	46	38	42	35	28	28	24	19	15	13	9	6
2.4	82	68	58	48	67	61	52	43	54	45	37	42	35	27	28	24	19	14	13	9	6
2.5	82	68	57	47	67	61	51	42	53	44	36	41	34	27	27	23	18	14	13	9	6
2.6	82	67	56	46	66	60	50	41	53	43	35	41	34	26	27	23	18	13	13	9	5
2.7	82	66	55	45	66	60	49	40	52	43	34	41	33	26	27	23	18	13	13	9	5
2.8	81	66	54	44	66	59	48	39	52	42	33	41	33	25	27	23	18	13	13	9	5
2.9	81	65	53	43	65	58	48	38	51	41	33	40	33	25	27	23	17	12	13	9	5
3.0	81	64	52	42	65	58	47	38	51	40	32	40	32	24	27	22	17	12	13	8	5
3.1	80	64	51	41	64	57	46	37	50	40	31	40	32	24	27	22	17	12	13	8	5
3.2	80	63	50	40	64	57	45	36	50	39	30	40	31	23	27	22	16	11	13	8	5
3.3	80	62	49	39	64	56	44	35	49	39	30	39	31	23	27	22	16	11	13	8	5
3.4	80	62	48	38	63	56	44	34	49	38	29	39	31	22	27	22	16	11	13	8	5
3.5	79	61	48	37	63	55	43	33	48	38	29	39	30	22	26	22	16	11	13	8	5
3.6	79	60	47	36	62	54	42	33	48	37	28	39	30	21	26	21	15	10	13	8	5
3.7	79	60	46	35	62	54	42	32	48	37	27	38	30	21	26	21	16	10	13	8	4
3.8	79	59	45	35	62	53	41	31	47	36	27	38	29	21	26	21	15	10	13	8	4
3.9	78	59	45	34	61	53	40	30	47	36	26	38	29	20	26	21	16	10	13	8	4
4.0	78	58	44	33	61	52	40	30	46	35	26	38	29	20	26	21	15	9	13	8	4
4.1	78	57	43	32	60	52	39	29	46	35	25	37	28	20	26	21	14	9	13	8	4
4.2	78	57	43	32	60	51	39	29	46	34	25	37	28	19	26	20	14	9	13	8	4
4.3	78	56	42	31	60	51	38	28	45	34	25	37	28	19	26	20	14	9	13	8	4
4.4	77	56	41	30	59	51	38	28	45	34	24	37	27	19	26	20	14	8	13	8	4
4.5	77	55	41	30	59	50	37	27	45	33	24	37	27	19	25	20	14	8	14	8	4
4.6	77	55	40	29	59	50	37	26	44	33	24	36	27	18	25	20	14	8	14	8	4
4.7	77	54	40	29	58	49	36	26	44	33	23	36	26	18	25	20	13	8	14	8	4
4.8	76	54	39	28	58	49	36	25	44	32	23	36	26	18	25	19	13	8	14	8	4
4.9	76	53	38	28	58	49	35	25	44	32	23	36	26	18	25	19	13	7	14	8	4
5.0	76	53	38	27	57	48	35	25	43	32	22	36	26	17	25	19	13	7	14	8	4

Step 2. See table below and the figure above.
This step involves determining the cavity ratios of the room, either by calculation or from the table.

Cavity Ratios

Room Dimensions		Cavity Depth																			
Width	Length	1.0	1.5	2.0	2.5	3.0	3.5	4.0	5.0	6.0	7.0	8	9	10	11	12	14	16	20	25	30
8	8	1.2	1.9	2.5	3.1	3.7	4.4	5.0	6.2	7.5	8.8	10.0	11.2	12.5	–	–	–	–	–	–	–
	10	1.1	1.7	2.2	2.8	3.4	3.9	4.5	5.6	6.7	7.9	9.0	10.1	11.3	12.4	–	–	–	–	–	–
	14	1.0	1.5	2.0	2.5	3.0	3.4	3.9	4.9	5.9	6.9	7.8	8.8	9.7	10.7	11.7	–	–	–	–	–
	20	0.9	1.3	1.7	2.2	2.6	3.1	3.5	4.4	5.2	6.1	7.0	7.9	8.8	9.6	10.5	12.2	–	–	–	–
	30	0.8	1.2	1.6	2.0	2.4	2.8	3.2	4.0	4.7	5.5	6.3	7.1	7.9	8.7	9.5	11.0	–	–	–	–
	40	0.7	1.1	1.5	1.9	2.3	2.6	3.0	3.7	4.5	5.3	5.9	6.5	7.4	8.1	8.8	10.3	11.8	–	–	–
10	10	1.0	1.5	2.0	2.5	3.0	3.5	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	–	–	–	–	–
	14	0.9	1.3	1.7	2.1	2.6	3.0	3.4	4.3	5.1	6.0	6.9	7.8	8.6	9.5	10.4	12.0	–	–	–	–
	20	0.7	1.1	1.5	1.9	2.3	2.6	3.0	3.7	4.5	5.3	6.0	6.8	7.5	8.3	9.0	10.5	12.0	–	–	–
	30	0.7	1.0	1.3	1.7	2.0	2.3	2.7	3.3	4.0	4.7	5.3	6.0	6.8	7.3	8.0	9.4	10.6	–	–	–
	40	0.6	0.9	1.2	1.6	1.9	2.2	2.5	3.1	3.7	4.4	5.0	5.6	6.2	6.9	7.5	8.7	10.0	12.5	–	–
	60	0.6	0.9	1.2	1.5	1.7	2.0	2.3	2.9	3.5	4.1	4.7	5.3	5.9	6.5	7.1	8.2	9.4	11.7	–	–
12	12	0.8	1.2	1.7	2.1	2.5	2.9	3.3	4.2	5.0	5.8	6.7	7.5	8.4	9.2	10.0	11.7	–	–	–	–
	18	0.7	1.1	1.5	1.8	2.2	2.5	2.9	3.6	4.4	5.1	5.8	6.5	7.2	8.0	8.7	10.2	11.6	–	–	–
	24	0.6	0.9	1.2	1.6	1.9	2.2	2.6	3.1	3.7	4.4	5.0	5.6	6.2	6.9	7.5	8.7	10.0	12.5	–	–
	36	0.6	0.8	1.1	1.4	1.7	1.9	2.2	2.8	3.3	3.9	4.4	5.0	5.5	6.0	6.6	7.8	8.8	11.0	–	–
	50	0.5	0.8	1.0	1.3	1.5	1.8	2.1	2.6	3.1	3.6	4.1	4.6	5.1	5.6	6.2	7.2	8.2	10.2	–	–
	70	0.5	0.7	1.0	1.2	1.5	1.7	2.0	2.4	2.9	3.4	3.9	4.4	4.9	5.4	5.8	6.8	7.8	9.7	12.2	–
14	14	0.7	1.1	1.4	1.8	2.1	2.5	2.9	3.6	4.3	5.0	5.7	6.4	7.1	7.8	8.5	10.0	11.4	–	–	–
	20	0.6	0.9	1.2	1.5	1.8	2.1	2.4	3.0	3.6	4.2	4.9	5.5	6.1	6.7	7.3	8.6	9.8	12.3	–	–
	30	0.5	0.8	1.0	1.3	1.6	1.8	2.1	2.6	3.1	3.7	4.2	4.7	5.2	5.8	6.3	7.3	8.4	10.5	–	–
	42	0.5	0.7	1.0	1.2	1.4	1.7	1.9	2.4	2.9	3.3	3.8	4.3	4.7	5.2	5.7	6.7	7.6	9.5	11.9	–
	60	0.4	0.7	0.9	1.1	1.3	1.6	1.8	2.2	2.6	3.1	3.5	3.9	4.4	4.8	5.2	6.1	7.0	8.8	10.9	–
	90	0.4	0.6	0.8	1.0	1.2	1.4	1.6	2.0	2.5	2.9	3.3	3.7	4.1	4.5	5.0	5.8	6.6	8.3	10.3	12.4
17	17	0.6	0.9	1.2	1.5	1.8	2.1	2.3	2.9	3.5	4.1	4.7	5.3	5.9	6.5	7.0	8.2	9.4	11.7	–	–
	25	0.5	0.7	1.0	1.2	1.5	1.7	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	7.0	8.0	10.0	12.5	–
	35	0.4	0.7	0.9	1.1	1.3	1.5	1.7	2.2	2.6	3.1	3.5	3.9	4.4	4.8	5.2	6.1	7.0	8.7	10.9	–
	50	0.4	0.6	0.8	1.0	1.2	1.4	1.6	2.0	2.4	2.8	3.1	3.5	3.9	4.3	4.5	5.4	6.2	7.7	9.7	11.6
	80	0.4	0.5	0.7	0.9	1.1	1.2	1.4	1.8	2.1	2.5	2.9	3.3	3.6	4.0	4.3	5.1	5.8	7.2	9.0	10.9
	120	0.3	0.5	0.7	0.8	1.0	1.2	1.3	1.7	2.0	2.3	2.7	3.0	3.4	3.7	4.0	4.7	5.4	6.7	8.4	10.1
20	20	0.5	0.7	1.0	1.2	1.5	1.7	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	7.0	8.0	10.0	12.5	–
	30	0.4	0.6	0.8	1.0	1.2	1.5	1.7	2.1	2.5	2.9	3.3	3.7	4.1	4.5	4.9	5.8	6.6	8.2	10.3	12.4
	45	0.4	0.5	0.7	0.9	1.1	1.3	1.4	1.8	2.2	2.5	2.9	3.3	3.6	4.0	4.3	5.1	5.8	7.2	9.1	10.9
	60	0.3	0.5	0.7	0.8	1.0	1.2	1.3	1.7	2.0	2.3	2.7	3.0	3.4	3.7	4.0	4.7	5.4	6.7	8.4	10.1
	90	0.3	0.5	0.6	0.8	0.9	1.1	1.2	1.5	1.8	2.1	2.4	2.7	3.0	3.3	3.6	4.2	4.8	6.0	7.5	9.0
	150	0.3	0.4	0.6	0.7	0.8	1.0	1.1	1.4	1.7	2.0	2.3	2.6	2.9	3.2	3.4	4.0	4.6	5.7	7.2	8.6
24	24	0.4	0.6	0.8	1.0	1.2	1.5	1.7	2.1	2.5	2.9	3.3	3.7	4.1	4.5	5.0	5.8	6.7	8.2	10.3	12.4
	32	0.4	0.6	0.7	0.9	1.1	1.3	1.5	1.8	2.2	2.6	2.9	3.3	3.6	4.0	4.3	5.1	5.8	7.2	9.0	11.0
	50	0.3	0.5	0.6	0.8	0.9	1.1	1.2	1.5	1.8	2.2	2.5	2.8	3.1	3.4	3.7	4.4	5.0	6.2	7.8	9.4
	70	0.3	0.4	0.5	0.7	0.8	1.0	1.1	1.4	1.7	2.0	2.2	2.5	2.8	3.0	3.3	3.8	4.4	5.5	6.9	8.2
	100	0.3	0.4	0.5	0.6	0.8	0.9	1.0	1.3	1.6	1.8	2.1	2.4	2.6	2.9	3.1	3.7	4.2	5.2	6.5	7.9
	160	0.2	0.4	0.5	0.6	0.7	0.8	1.0	1.2	1.4	1.7	1.9	2.1	2.4	2.6	2.8	3.3	3.8	4.7	5.9	7.1

30	30	0.3	0.5	0.7	0.8	1.0	1.2	1.3	1.7	2.0	2.3	2.7	3.0	3.3	3.7	4.0	4.7	5.4	6.7	8.4	10.0
	45	0.3	0.4	0.6	0.7	0.8	1.0	1.1	1.4	1.7	1.9	2.2	2.5	2.7	3.0	3.3	3.8	4.4	5.5	6.9	8.2
	60	0.3	0.4	0.5	0.6	0.7	0.9	1.0	1.2	1.5	1.7	2.0	2.2	2.5	2.7	3.0	3.5	4.0	5.0	6.2	7.4
	90	0.2	0.3	0.4	0.6	0.7	0.8	0.9	1.1	1.3	1.6	1.8	2.0	2.2	2.5	2.7	3.1	3.6	4.5	5.6	6.7
	150	0.2	0.3	0.4	0.5	0.6	0.7	0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.8	3.2	4.0	5.0	5.9
	200	0.2	0.3	0.4	0.5	0.6	0.7	0.8	1.0	1.1	1.3	1.5	1.7	1.9	2.0	2.2	2.6	3.0	3.7	4.7	5.6
36	36	0.3	0.4	0.6	0.7	0.8	1.0	1.1	1.4	1.7	1.9	2.2	2.6	2.8	3.0	3.3	3.9	4.4	5.5	6.9	8.3
	50	0.2	0.4	0.5	0.6	0.7	0.8	1.0	1.2	1.4	1.7	1.9	2.1	2.5	2.6	2.9	3.3	3.8	4.8	5.9	7.2
	75	0.2	0.3	0.4	0.5	0.6	0.7	0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.3	2.5	2.9	3.3	4.1	5.1	6.1
	100	0.2	0,3	0.4	0.5	0.6	0.7	0.8	0.9	1.1	1.3	1.5	1.7	1.9	2.1	2.3	2.6	3.0	3.8	4.7	5.7
	150	0.2	0.3	0.3	0.4	0.5	0.6	0.7	0.9	1.0	1.2	1.4	1.6	1.7	1.9	2.1	2.4	2.8	3.5	4.3	5.2
	200	0.2	0.2	0.3	0.4	0.5	0.6	0.7	0.8	1.0	1.1	1.3	1.5	1.6	1.8	2.0	2.3	2.6	3.3	4.1	4.9
42	42	0.2	0.4	0.5	0.6	0.7	0.8	1.0	1.2	1.4	1.6	1.9	2.1	2.4	2.6	2.8	3.3	3.8	4.7	5.9	7.1
	60	0.2	0.3	0.4	0.5	0.6	0.7	0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.8	3.2	4.0	5.0	6.0
	90	0.2	0.3	0.3	0.4	0.5	0.6	0.7	0.9	1.0	1.2	1.4	1.6	1.7	1.9	2.1	2.4	2.8	3.5	4.4	5.2
	140	0.2	0.2	0.3	0.4	0.5	0.5	0.6	0.8	0.9	1.1	1.2	1.4	1.5	1.7	1.9	2.2	2.5	3.1	3.9	4.6
	200	0.1	0.2	0.3	0.4	0.4	0.5	0.6	0.7	0.9	1.0	1.1	1.3	1.4	1.6	1.7	2.0	2.3	2.9	3.6	4.3
	300	0.1	0.2	0.3	0.3	0.4	0.5	0.5	0.7	0.8	0.9	1.1	1.3	1.4	1.5	1.7	1.9	2.2	2.8	3.5	4.2
50	50	0.2	0.3	0.4	0.5	0.6	0.7	0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.8	3.2	4.0	5.0	6.0
	70	0.2	0.3	0.3	0.4	0.5	0.6	0.7	0.9	1.0	1.2	1.4	1.5	1.7	1.9	2.0	2.4	2.7	3.4	4.3	5.1
	100	0.1	0.2	0.3	0.4	0.4	0.5	0.6	0.7	0.9	1.0	1.2	1.3	1.5	1.6	1.8	2.1	2.4	3.0	3.7	4.5
	150	0.1	0.2	0.3	0.3	0.4	0.5	0.5	0.7	0.8	0.9	1.1	1.2	1.3	1.5	1.6	1.9	2.1	2.7	3.3	4.0
	300	0.1	0.2	0.2	0.3	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.3	1.4	1.6	1.9	2.3	2.9	3.5
60	60	0.2	0.2	0.3	0.4	0.5	0.6	0.7	0.8	1.0	1.2	1.3	1.5	1.7	1.8	2.0	2.3	2.7	3.3	4.2	5.0
	100	0.1	0.2	0.3	0.3	0.4	0.5	0.5	0.7	0.8	0.9	1.1	1.2	1.3	1.5	1.6	1.9	2.1	2.7	3.3	4.0
	150	0.1	0.2	0.2	0.3	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.2	1.3	1.4	1.6	1.9	2.3	2.9	3.5
	300	0.1	0.1	0.2	0.2	0.3	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.4	1.6	2.0	2.5	3.0
75	75	0.1	0.2	0.3	0.3	0.4	0.5	0.5	0.7	0.8	0.9	1.1	1.2	1.3	1.5	1.6	1.9	2.1	2.7	3.3	4.0
	120	0.1	0.2	0.2	0.3	0.3	0.4	0.4	0.5	0.6	0.8	0.9	1.0	1.1	1.2	1.3	1.5	1.7	2.2	2.7	3.3
	200	0.1	0.1	0.2	0.2	0.3	0.3	0.4	0.5	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.3	1.5	1.8	2.3	2.7
	300	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.4	0.5	0.5	0.7	0.7	0.8	0.9	1.0	1.1	1.3	1.7	2.1	2.5
100	100	0.1	0.1	0.2	0.2	0.3	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.4	1.6	2.0	2.5	3.0
	200	0.1	0.1	0.1	0.2	0.2	0.3	0.3	0.4	0.4	0.5	0.6	0.7	0.7	0.8	0.9	1.0	1.2	1.5	1.9	2.2
	300	0.1	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.4	0.5	0.5	0.6	0.7	0.7	0.8	0.9	1.1	1.3	1.7	2.0
150	150	0.1	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.4	0.5	0.5	0.6	0.7	0.7	0.8	0.9	1.1	1.3	1.7	2.0
	300	–	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.4	0.5	0.5	0.6	0.6	0.7	0.8	1.0	1.2	1.5
200	200	–	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.4	0.5	0.5	0.5	0.6	0.7	0.8	1.0	1.2	1.5
	300	–	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.4	0.4	0.5	0.5	0.6	0.7	0.8	1.0	1.2
300	300	–	–	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.3	0.4	0.4	0.5	0.5	0.6	0.7	0.8
500	500	–	–	–	–	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.4	0.5	0.6

The basic expression for a cavity ratio (CR) is

$$CR = 2.5 \times \frac{\text{area of cavity wall}}{\text{area of work plane}}$$

In a rectangular space the area of the cavity wall is
hx(21 2w) or 2h(1 w); therefore

$$CR = \frac{2.5 \times 2h \times (L + W)}{\text{area of work plane}}$$

or

$$CR = 5h \times \frac{L + W}{L \times W}$$

For other than rectangular rooms, the area can be calculated as required. For instance, in a circular room, the activity wall area = h × 2 r and the work plane area is r^2.
Thus

$$CR = \frac{2.5 \times h \times 2r}{r^2} = \frac{5h}{r}$$

for each of the cavities in rectangular room we have:

a.) Ceiling Cavity Ratio, CCR

$$CCR = 5h_{cc} \frac{L + W}{L \times W}$$

b.) Room Cavity Ratio, RCR

$$RCR = 5h_{re} \frac{L + W}{L \times W}$$

c.) Floor Cavity Ratio, FCR

$$FCR = 5h_{cc} \frac{L + W}{L \times W}$$

Most people prefer, for rectangular rooms, to use the table on cavity ratio rather than formulas. For reference since all the CR figures are related, having determined one, the others are

$$CCR = RCR \frac{h_{cc}}{h_{rc}}$$

$$FCR = RCR \frac{h_{fc}}{h_{rc}}$$

$$CCR = FCR \frac{h_{cc}}{h_{fc}}$$

Step 3. See table on step 1, re:,Percent effective ceiling or floor cavity reflectance and the sectional drawing. This step involves obtaining the effective ceiling reflectance (P_{cc}) from the table. Note that the wall reflectance remains as selected in step 1. If the fixtures are surface mounted or recessed, then CCR = O and P_{cc} = selected ceiling reflectance

Step 4. See table as above and the sectional figure. The step involves obtaining the effective floor reflectance P_{cc} as above in step 3 for P_{cc}.

Step 5. Select CU from manufacturer's data (coefficient of utilization).

Step 6. Calculate footcandles and number of fixtures or area per luminaire in the usual fashion.

Illustrative Examples

Given: classroom; 20 × 25 × 12 ft. Elementary school
(6.00 × 7.50 × 3.60 M)

Initial Reflectances; ceiling 80, wall 50, floor 20.
Provide adequate lighting using fluorescent lamp fixtures.
Assume yearly maintenance, lamp replacement at 70% life, proper voltage and ballasts, medium clean atmosphere.

SOLUTION: From the table below, the required illumination level for pencil writing is 70 fc ESI

Illumination Levels

	Recommended Minimum Footcandles
Industrial	
Airplane Manufacturing	
Parts manufacturing	
Drilling, riveting, and screw fastening	70
Final assembly	100
Airplane Hangars	
Repair service only	100
Assembly	
Rough easy seeing	30
Medium	100
Fine	500
Bakeries	
Mixing room	50
Oven room	30
Book Binding	
Cutting, punching, and stitching	70
Embossing and inspecting	200
Chemical Works	
Hand furnaces, boiling tanks, stationary driers, stationary and gravity crystallizers.	30
Clay Products and Cements	
Molding, pressing, cleaning, and trimming	30
Color and glazing—rough work	100

	Recommended Minimum Footcandles
Garages—Automobile and Truck	
Service garages	
Repairs	100
Active traffic areas	20
Parking garages	
Entrance	50
Traffic lanes	10
Storage	5
Inspection	
Ordinary	50
Difficult	100
Highly difficult	200
Most difficult	1000
Laundries	
Washing	30
Flatwork ironing, weighing, listing, and marking	50
Machine and press finishing, sorting	70
Leather Manufacturing	
Cleaning, tanning, and stretching, vats	30
Finishing and scarfing	100
Locker Rooms	20
Machine Shops	
Rough bench and machine work	50
Medium bench and machine work	100
Fine bench and machine work, fine automatic machines	500

Cloth Products	
Cloth inspection	2000
Cutting	300
Sewing	500
Electrical Equipment Manufacturing	
Insulating: coil winding	100
Testing	100
Exterior Areas	
Entrances	
Active (pedestrian and/or conveyance)	5
Inactive (normally locked, infrequently used)	1
Building surrounds	1
Active shipping area	5
Storage areas—active	20
Storage areas—inactive	1
Loading and unloading platforms	20
Sheet Metal Works	
Miscellaneous machines, ordinary bench work	50
Presses, shears, stamps, spinning, medium bench work	50
Punches	50
Stairways, Corridors, and Other Service Areas	20
Storage Rooms or Warehouses	
Inactive	5
Active	
Rough, bulky	10
Fine	50
Testing	
General	50
Extra fine instruments, scales, etc.	200
Toilets and Washrooms	30
Upholstering—Automobile, Coach, Furniture	100
Watch and Jewelry Manufacturing	500
Warehouse (see Storage)	
Welding	
General illumination	50
Precision manual arc welding	1000
Woodworking	
Rough sawing and bench work	30
Sizing, planing, rough sanding, medium quality machine and bench work, glueing, veneering, cooperage	50
Fine bench and machine work, fine sanding, and finishing	100

Materials Handling	
Wrapping, packing, labeling	50
Picking stock, classifying	30
Loading, trucking	20
Inside truck bodies and freight cars	10
Paint Shops	
Dipping, simple spraying firing	50
Fine hand painting and finishing	100
Polishing and Burnishing	100
Printing Industries	
Printing plants	
Color inspection and appraisal	200
Composition	100
Presses	70
Proof reading	150
Receiving and Shipping (see Materials Handling)	
Exhibitions	30
Social activities	5
Banks (see also Offices)	
Lobby	50
Writing areas in lobby	70[a]
Teller's stations, posting, keypunch	150[a]
Barber and Beauty Shops	100
Churches & Synagogues	
Altar, arc	100
Pews	15
Pulpit (supplementary)	50
Club Reading Rooms	30
Courtrooms	
Seating area	30
Court activity area	70[a]
Hospitals	
Autopsy	
General	100
Supplementary	1000
Corridors	20
Emergency Rooms	
General	100
Local	2000
Examination and Treatment Rooms	
General	50
Examining table	100
Laboratories	
General	50
Closework	100
Patients' Rooms	
General	20
Supplementary for reading	30
Supplementary for examination	100
Recovery Rooms	30
Surgery	

	Recommended Minimum Footcandles
Stores, Offices, and Institutions	
Art Galleries	
General	30
On paintings (supplementary)	30
Dark paintings with fine detail may require two or three times as much illumination.	
On statuary	100
In some cases, much more illumination is necessary to reveal the beauty of statuary.	
Auditoriums	
Assembly only	15
General	10
Corridors, elevators, and stairs	20
Entrance foyer	30
Linen room	
Sewing	100
General	20
Lobby	
General lighting	10
Reading and working areas	30
Power Plant	
Boiler room	10
Equipment room	20
Storerooms	10
Libraries	
Reading rooms and carrells	70[a]
Stacks	30
Book repair and binding	70
Check-in and check-out, catalogs,	70[a]
Card files	100[a]
Offices	
General	
Cartography, designing, detailed drafting	200[a]
Accounting, auditing, tabulating, bookkeeping, business machine operation	150[a]
Regular Office Work	
Good copy	70[a]
Regular office work—reading, transcribing, active filling, mail sorting, etc., fair-quality copy	100[a]
Corridors, elevators, escalators, stairways	20
(Or, not less than $\frac{1}{5}$ the level in adjacent areas.)	
Post Offices	
General	200
Supplementary on table	2500
Toilets	20
Waiting Rooms	20
Hotels and Motels	
Bars and cocktail lounges (see Restaurants)	
Bathrooms	
General	10
Mirror	30
Bedrooms	
Reading (books, magazines, newspapers)	30
Subdued environment	15
Quick service type	
Bright surroundings	100
Normal surroundings	50
NOTE: Footcandle levels in dining areas are highly variable. Variations depend on such factors as time of day, desired atmosphere, individuality, and attractiveness.	
Food Displays—twice the general levels but not under	50
Kitchen—commercial, hospital, hotel	
Inspection, checking, and pricing	70
Other areas	30
Schools	
Tasks	
Reading printed material	30[a]
Reading pencil writing	70[a]
Reading spirit duplicated material	
Good copy	30[a]
Poor copy	100[a]
Classrooms	
Chalkboards (supplementary illumination)	150
Drafting rooms	100[a]
Laboratories	100
Lecture rooms	
General	70[a]
Special exhibits and demonstrations	150
Lipreading classes	150
Shops	100
Sewing rooms	150
Sightsaving classes	150[a]
Study halls	70[a]
Corridors and stairs	20
Stores	

Illumination Levels (Continued)

	Recommended Minimum Footcandles
Post Offices	
Lobby, on tables	30
Sorting, mailing, etc.	100
Storage	20
Corridors and stairways	20
Restaurants	
Dining Areas	
Cashier	50
Intimate type	
Light environment	10
Subdued environment	3
Leisure type	
Light environment	30
Theaters	
Auditoriums	
During intermission	5
During performance or presentation	0.1
Foyer	5
Entrance lobby	20
Residential (see Table 000 p. 000)	
Outdoor Floodlighting	
Building	
Construction	10
Excavation	2

Bulletins and Poster Panels

	Surroundings Dark	Surroundings Bright
Light surfaces	20	50
Dark surfaces	50	100

	Recommended Minimum Footcandles
Stores	
Store interiors	
Circulation areas	30
Merchandising areas	
Service stores	100
Self-service stores	200
Showcases and wall cases	
Service stores	200
Self-service stores	500
Feature displays	
Service stores	500
Self-service stores	1000
Stockrooms	30

Building Exteriors, and Monuments (Floodlighted)

	Surroundings Dark	Surroundings Bright
Light surfaces	5	15
Medium—dark surfaces	15	30
Dark surfaces	20	50

Flags	50
Parking Lots	
Self-parking	1
Attendant parking	2
Shopping centers (customer attraction device)	5

We select from the table on wall luminance coefficients (previous pages), fixture no. 23 for two lamps, which has semi-direct distribution, low brightness for high VCP (students spend a large proportion of their time in heads-up position, requiring high VCP), batwing type crosswise distribution for high CRF and low veiling reflection, and good CU which means high efficiency and low energy use. Furthermore, maintenance category LI is excellent as in the wide lateral spacing possible with the 1.5 s/MH listed. Arrangement of fixtures will be in rows, front-to-back. Based on experience, we would here design for 80 raw fc to obtain the requisite 70-fc, Esl average.

Calculations

Step 1. From the table below, assume 24-in. stem length (in lieu of 21 in., for ease of calculation). Also assume standard working plane as 30 in. AFF. Therefore:

$$hcc = 2.0 \qquad hrc = 7.5 \qquad hfc = 2.5$$
$$P_c = 80\% \qquad P_w = 50 \qquad P_f = 20\%$$

Table 20.6 ***A Lighting Efficiency Comparison for Common Fluorescent Fixtures***

Fixture Description	Flux Distribution	Effective[a] Lumens per Watt
1. Recessed, 2 × 4 ft, four-lamp, static, metal troffer; synthetic enameled, 0.91 reflectance, with clear prismatic acrylic lens, without diffusing overlay.	Radial batwing	15.1
2. Recessed, 2 × 4 ft, four-lamp static, metal troffer; synthetic enameled, 0.88 reflectance, with clear acrylic prismatic lens, with 0.40-in. diffusing overlay.	Linear batwing	15.3
3. Recessed, 1 × 4 ft, two-lamp, air-handling, metal troffer with semispecular, anodized aluminum parabolic reflector and louvers (crosswise only).	Linear batwing, low brightness	27.5
4. Recessed, 2 × 4 ft, four-lamp, air-handling, metal troffer, with baked enamel reflector, 0.91 reflectance, with semispecular anodized aluminum parabolic louvers (crosswise and lengthwise).	Linear batwing	28.3
5. Recessed, 2 × 4 ft, four-lamp, static, metal troffer; baked enamel, 0.87 reflectance, with clear acrylic prismatic lens, without overlay.	General prismatic	30.3
6. Same as 5 above except 2 × 4 ft two-lamp.	General prismatic	30.5
7. Same as 5 with clear, acrylic, low-brightness prismatic lens without overlay.	Low brightness	32.5
8. Recessed, 1 × 4 ft, two-lamp, static, metal troffer enameled; 0.88 reflectance, with specular Alzac parabolic louvers.	Low brightness	37.1

Step 2. from formulas

$$RCR = 5h_{rc}\left(\frac{L + W}{L \times W}\right)$$

$$= 5(7.5)\left(\frac{45}{500}\right) = 3.375$$

Similarly

$$CCR = 5(2)\left(\frac{45}{500}\right) = 0.9$$

$$FCR = 5(2.5)\left(\frac{45}{500}\right) = 1.125$$

Step 3. From table of step 1 (percent effective ceiling or floor cavity reflectance)

$$P_{cc} = 68$$

Step 4. By interpolation between 10 and 30 floor reflectances and 1.1 and 1.2 cavity ratio, we obtain

$$fc = 19 \text{ and } {}_{W} = 50\% \text{ as given}$$

Step 5. By double interpolation

	CU		
Pcc	70	68	50
RCR = 3	0.58		0.54
3.375	0.549	0.545	0.509
RCR = 4	0.53		0.49
therefore, CU =	0.545		

Step 6. Light Loss factors see figure below

GENERAL INFORMATION

Project identification: BRIGHT CHILD ELEMENTARY SCHOOL
(Give name of area and/or building and room number)

Average maintained illumination for design: (1) footcandles

Luminaire data:

Manufacturer: ANY GOOD

Catalog number: 000

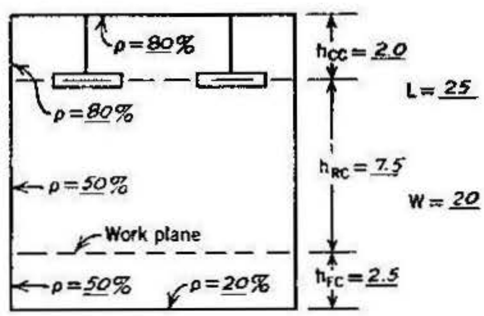
Lamp Data:

Type and color: F40T12 CW

Number per luminaire: 2

Total lumens per luminaire: 6400

SELECTION OF COEFFICIENT OF UTILIZATION



Step 1: Fill in sketch at right.

Step 2: Determine Cavity Ratios from Fig. 20.34, or by formulas.

Room Cavity Ratio, RCR = 3.375

Ceiling Cavity Ratio, CCR = 0.9

Floor Cavity Ratio, FCR = 1.125

Step 3: Obtain effective ceiling cavity reflectance (ρ_{CC}) from Table 20.9 ρ_{CC} = 68%

Step 4: Obtain effective floor cavity reflectance (ρ_{FC}) from Table 20.9 ρ_{FC} = 19%

Step 5: Obtain coefficient of utilization (CU) from manufacturer's data. CU = 0.545

SELECTION OF LIGHT LOSS FACTORS

Unrecoverable		Recoverable	
Luminaire ambient temperature	1.0	Room surface dirt depreciation	0.9
Voltage to luminaire	1.0	Lamp lumen depreciation	0.9
Ballast factor	1.0	Lamp burnouts factor	1.0
Luminaire surface depreciation	0.9	Luminaire dirt depreciation LDD	0.9

Total light loss factor, LLF (product of individual factors above): 0.656

CALCULATIONS

(Average Maintained Illumination Level)

$$\text{Number of Luminaires} = \frac{(\text{Footcandles}) \times (\text{Area in square feet})}{(\text{Lumens per luminaire}) \times (\text{CU}) \times (\text{LLF})}$$

$$= \frac{30 \times 20 \times 25}{6400 \times 0.545 \times 0.656} = 17.48$$

$$\text{Footcandles} = \frac{(\text{Number of luminaires}) \times (\text{Lumens per luminaire}) \times (\text{CU}) \times (\text{LLF})}{(\text{Area in square feet})}$$

= See text =

Calculated by: B. STEIN Date: MAR. '78

(1) 70 ESI, 80 raw

$$\text{LLF} = 0.9 \times 0.9 \times 0.9 \times 0.9 = 0.656$$

Step 7. Footcandle calculations:

$$\text{Number of Luminaires} = \frac{80 \times 20 \times 25}{2 \times 3200 \times 0.545 \times 0.656}$$

$$= 17.48 \text{ fixtures}$$

16

LIGHTING APPLICATION

LIGHTING APPLICATION

RESIDENTIAL LIGHTING

a) **Energy Considerations**

1. Provide means for reducing light levels in all areas. A kitchen during food preparation does not have the same lighting requirements as kitchen being entered for a "refrigerator raid." Low-level lighting provision should be made in all rooms, including bathrooms. To accomplish this use high – low switches, simple dimmers, multilevel ballast, and multilevel switching. An ancillary benefit is that ambience can be changed thereby in multiuse rooms such as dining rooms, family rooms, and finished basements.

2. Provide local task lighting for difficult tasks such as the location at which family accounts are handled.

3. Provide switching for accent lighting.

4. In large residences consider low-voltage control for its ease of remote control. Considerable energy savings can be effected in this way.

5. Provide time switches for exterior lights,

6. Use daylight in areas normally occupied during daylight hours such as kitchens and living rooms. Consider skylights with built-in artificial lighting for these areas.

b) **Sources**

When using fluorescent, choose proper color for space. See table shown. Despite their lower efficacy, use of daylight fluorescents as the artificial source in lighted skylights is very effective.

A Guide for Lamp Selection Based on General Color Rendering Properties

Type of Lamp	*Efficacy (lpw)*	*Lamp Appearance Effect on Neutral Surfaces*	*Effect on "Atmosphere"*	*Colors Strengthened*	*Colors Grayed*	*Effect on Complexions*	*Remarks*
				Fluorescent Lamps			
Cool white CW	High	White	Neutral to moderately cool	Orange, yellow, blue	Red	Pale pink	Blends with natural daylight—good color acceptance
Deluxe cool white CWX	Medium	White	Neutral to moderately cool	All nearly equal	None appreciably	Most natural	Best overall color rendition; simulates natural daylight

Warm[b] white WW	High	Yellowish white	Warm	Orange, yellow,	Red, green, blue	Sallow	Blends with incandescent light—poor color acceptance
Deluxe[b] warm white WWX	Medium	Yellowish white	Warm	Red, orange, yellow, green	Blue	Ruddy	Good color rendition; simulates incandescent light
Daylight	Medium-high	Bluish white	Very cool	Green, blue	Red, orange	Grayed	Usually replaceable with CW
White	High	Pale yellowish white	Moderately warm	Orange, yellow	Red, green, blue	Pale	Usually replaceable with CW or WW
Soft white/ natural	Medium	Purplish white	Warm pinkish	Red, orange	Green, blue	Ruddy pink	Tinted source usually replaceable with CWX or WWX
			Incandescent Lamps, Tungsten Halogen				
Incandescent filament	Low	Yellowish white	Warm	Red, orange, yellow	Blue	Ruddiest	Good color rendering
			High-Intensity Discharge Lamps				
Clear mercury	Medium	Greenish blue-white	Very cool, greenish	Yellow, blue, green	Red, orange	Greenish	Very poor color rendering
White mercury	Medium	Greenish white	Moderately cool, greenish	Yellow, green, blue	Red, orange	Very pale	Moderate color rendering
Deluxe white[a] mercury	Medium	Purplish white	Warm, purplish	Red, blue, yellow	Green	Ruddy	Color acceptance similar to CW fluorescent
Metal halide[a]	High	Greenish white	Moderately cool, greenish	Yellow, green, blue	Red	Grayed	Color acceptance similar to CW fluorescent
High-pressure sodium[b]	High	Yellowish	Warm, yellowish	Yellow green, orange	Red, blue	Yellowish	Color acceptance approaches that of WW fluorescent

Listed below are the appropriate sources to be used in different areas of a residence:

1. Work and utility areas including kitchens, laundry and workshop-fluorescent of appropriate color
2. Built-in architectural elements-fluorescent
3. Bedrooms, portable lamps, accent lights-incandescent, tungsten-halogen
4. Circulation areas, stairwells, closets-incandescent
5. Exterior: for short periods-incandescent; for long periods-HID
6. Bathrooms: General incandescent or warm white fluorescent; mirror lighting-incandescent

7. All rooms-daylight where possible
8. All spaces-use incandescent when source is turned on and off frequently or lighted for short periods only.

c) **Recommendations**

These are design recommendations which are applicable to residential occupancies of all types.

1. Use general/task — lighting concept with rocommended levels as in the tables below

Current Footcandle Recommendations for General Lighting

	Typical American Recommendation	*Other Authorities*
Activity or Area	*Footcandles[a] Minimum at Any Time*	*Average Footcandles*
Conversation and relaxation	10[a]	5–10
Passage areas	10[a]	5–10
Areas, other than kitchen	30	10–20
Kitchen	50	30

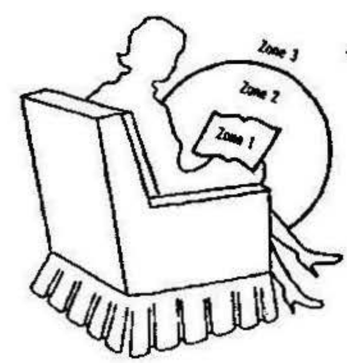
Current Footcandle Recommendations for Specific Visual Tasks[a]

	Typical American Recommendation	*Other Authorities*
Seeing Task	*Minimum Footcandles*	*Average Footcandles*
Dining	15	10–15
Grooming, Makeup	50	50
Handcraft		
Ordinary seeing tasks	70	20–40
Difficult seeing tasks	100	50–70
Critical seeing tasks	200	>125
Ironing	50	20–30
Kitchen Duties		
Food preparation and cleaning involving difficult seeing tasks	150	70–90
Serving and other noncritical tasks	50	20–30
Laundry Tasks		
Preparation, sorting, inspection	50	20–30
Washer and dryer areas	30	10–15
Reading and Writing		
Handwriting, reproductions, and poor copies	70	70
Books, magazines, and newspapers	30	30

Reading Piano Scores		
Advanced	70	50
Simple	30	30
Sewing, Hand or Machine		
Dark fabrics	200	>125
Medium fabrics	100	70–90
Light fabrics	50	30–50
Occasional—high contrast	30	10–20
Study	70	50–70
Table Games	30	30

These levels are based on young eyes with 20-20 vision. Older eyes, even when properly corrected by glasses, have reduced visual acuity, a longer period of adaptation, and decreased resistance to glare.

2. Provide brightness ratios as in this figure.



Zone 2	The immediate surroundings (area adjacent to the visual task)
Desirable ratio	1/3 to equal to task*
Minimum acceptable ratio	1/5 to equal to task*
Zone 3	**The general surroundings (not immediataly adjacent to task)**
Desirable ratio	1/5 to 5 times task*
Minimum acceptable ratio	1/10 to 10 times task*

*Typical task luminance range is 12 to 35 footlamberts (seldom exceeds 60 footlamberts)

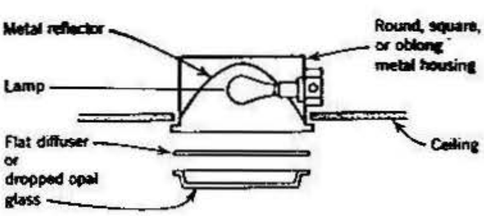
3. Provide general lighting in all spaces, sufficient for movement and casual seeing. Hallways require little lighting; Stairs require more. Light stairs from directly above or ahead to create a shadow directly above or ahead to create a shadow directly below the tread front. Lighting from front eliminates shadows and can create a safety hazard.

4. Do not avoid ceiling lights as is so frequently done. Wide-profile ceiling fixtures provide general lighting; switch-controlled table lamps do not.

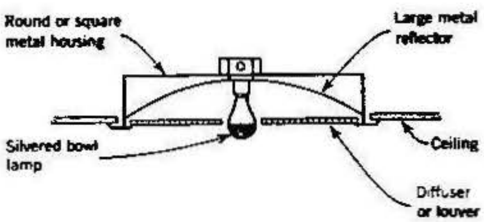
d) Fixtures and Luminous Elements

1. Utilize diffuse distribution for general lighting, narrow-distribution downlight for area and furniture accents, and narrow-distribution, ceiling-recessed incandescent wallwashers for accenting surfaces such as brick walls.

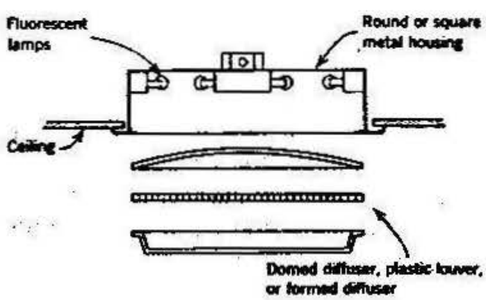
Wide Profile



For general illumination (almost always used in multiple). Basement, reacreation rooms, kitchens, laundries, halls (service). Used singly or in small groups for small areas such as walk-in closets, garage, entry doors, overnangs in porches. Because of high luminance of diffuser, seldom used in living or social areas.

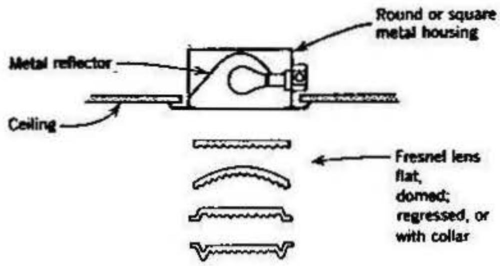


Used in multiple for general lighting in kitchens, baths, laundries, recreation rooms and family rooms. Used singly or in groups over game tables. Lower luminance allows this type of luminaire to be used in living areas if styling permits.

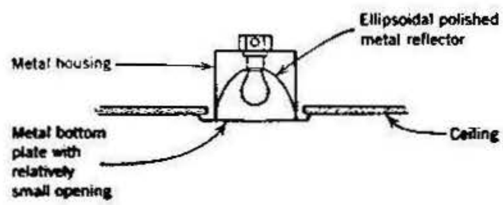


Very wide distribution, excellent as general lighting for kitchen, laundry, recreation room and bath. Because of large size and high lumen output, fewer units required. Often used signly or in pairs for entry halls and foyers and for skylight effect in interior halls and stairways.

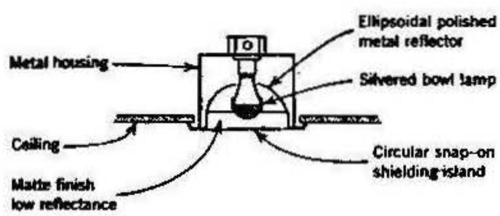
Medium Profile



Used for specific task lighting where task area is large, such as kitchen sink, kitchen island counter or range, laundry tubs and ironing, game table, workbench, hobby area. Used for general lighting in restricted areas such as halls, entries and baths. Multiple groupings are satisfactory for the general lighting of kitchens and recreation rooms. If weatherproof, appropriate for outdoor uses, including overhangs, porches, entries.



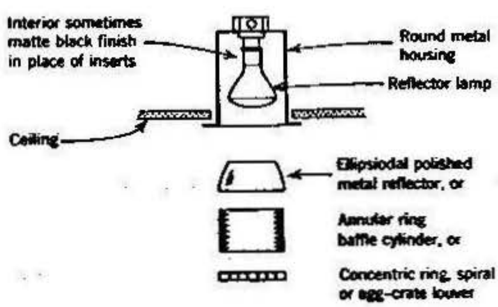
Uses basically the same as the Fresnel unit listed above, except that the lower luminance makes this type of equipment more usable in living and dining areas.



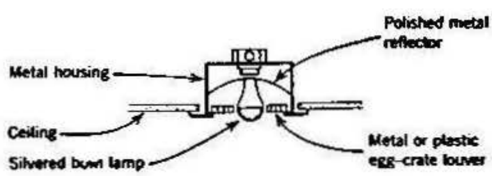
Same uses as open ellipsoidal unit listed above but has a far better control of lamp luminance.

Design features of recessed luminaires having wide, medium, narrow, and asymmetric profiles.

Narrow Profile

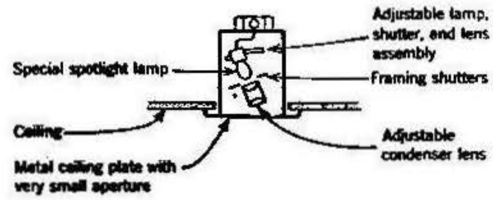


Accent lighting over plants, cocktail tables, etc. Wall lighting–mounted close to textured surfaces such as brick, stone, rough wood and fabrics. Task lighting–food preparation areas (may cause specular reflections), in multiple on quite close spacing for general lighting. Most effective when used near perimeter of room so that some light spills onto wall. Dramatic effects for family rooms, recreation rooms, and formal living areas. Supplementary stair lighting–shadow patterns define treads and risers. Dining tables–provide functional light on dining table to supplement decorative effect from hanging luminaire.

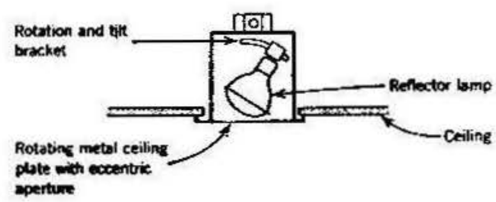


Same uses as type immediately above. Low luminance very desirable, but larger size sometimes prohibits use in highly styled interiors.

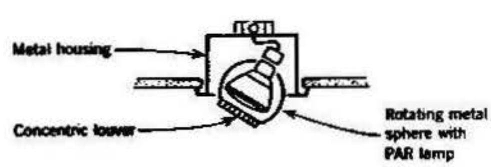
Special Asymmetric Profile



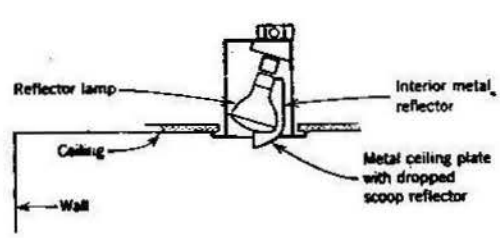
Adjustable beam can be framed precisely to outline paintings, pictures, maps, and niches. When aimed directly down, shutters can frame dining tables, cocktail or coffee tables, or other horizontal elements. Special high-light-output lamps providing controlled beams often used in these units. Should have easy access for the relamping required. Many come equipped with top-access openings for relamping from above.



Useful for gallery or picture lighting and to light sculpture. If scalloping effect is acceptable can be used for wall lighting and to accent fireplace surfaces. Large size of bottom aperture sometimes make this unacceptable for highly styled interiors. May also be used for lighting piano music and sewing machines.

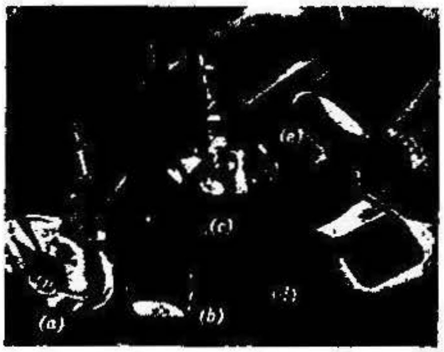


Same uses as recessed adjustable luminaire immediately above.

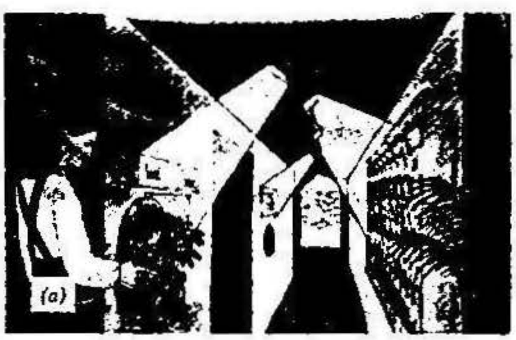


For uniform illumination of plane wall surfaces. Extremely effective for lighting murals and for minimizing wall imperfections. *Not* generally to be used for lighting textured wall surfaces because it directs no grazing light at wall. Spacing of these units is critical–follow manufacturer's recommendations closely.

2. Use built-in lighting to the extent possible, including architectural lighting elements. We believe that this demonstrates integrity of concept. For this reason, we recommend that the flexibility of track lighting be utilized for accent and task lighting but not for general lighting or as the lighting system throughout the residence.



Track lights are available in a wide variety of practical and decorative designs. Types (a) *and* (c) *use standard A-shape incandescent lamps;* (b) *and* (e) *are wood-grain finished and hold an 'R'-shape lamp;* (d) *is an adjustable wall wash unit using a 500-w tungsten-halogen lamp.* (f) *through* (i) *are decorative ball units holding R-lamps of different sizes. Courtesy of Lightcraft/Scovill.*



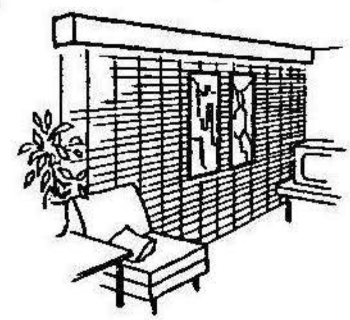
(a) *Since the primary objective of this lighting is display, track units offer the desired flexibility. Spill light is sufficient for walking through the corridor. When display is not required, one unit should be separately controlled to provide needed passage lighting.*

(b) *Track light provides needed task lighting for reading in bed or working at the desk. The remaining units should be separately controlled, since display lighting in a bedroom is hardly needed constantly. Illustrations Courtesy of Lightcraft/Scovill.*

3. Private residences are the exception to the rule of selecting off-the-shelf items in preference` to specials. The lighting should compliment the architecture and furnishings, and frequently this can best be accomplished by original designs.

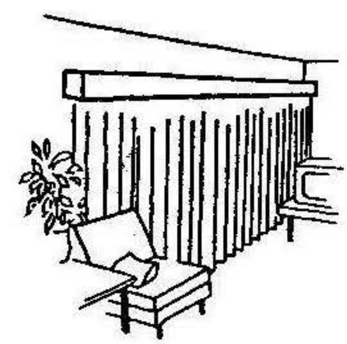
Architectural Lighting Elements

Reference to architectural lighting elements is usually made when dealing with coves, cornices, valances, coffers, skylights, or other luminous surfaces not normally comprising a lighting fixture. Although such units are inherently inefficient, their use is often indicated by architectural consideration, since they generally create an attractive indirect-lighting-source. Empirical design data given in these following figures.



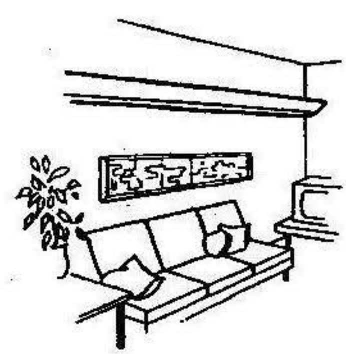
(a) Lighted Cornices

Cornices direct all their light downward to give dramatic interest to wall coverings, draperies, murals, etc. May also be used over windows where space above window does not permit valance lighting. Good for low-ceilinged rooms.



(b) Lighted Valances

Valances are always used at windows, usually with draperies. They provide up-light which reflects off ceiling for general room lighting and down-light for drapery accent. When closer to ceiling than 10 inches use closed top to eliminate annoying ceiling brightness.

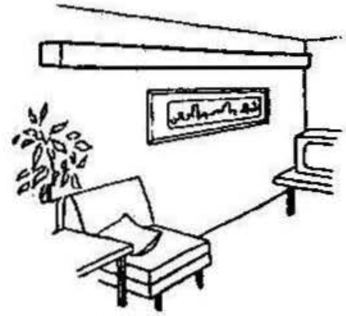


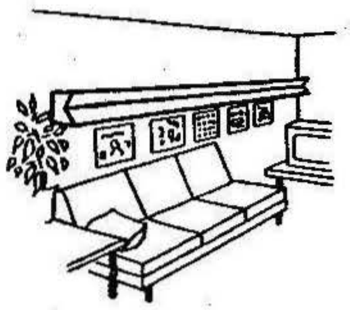
(c) Lighted Coves

Coves direct all light to the ceiling. Should be used only with white or near-white ceilings. Cove lighting is soft and uniform but lacks punch or emphasis. Best used to supplement other lighting. Suitable for high-ceilinged rooms and for places where ceiling heights abruptly change.

(d) Lighted High Wall Brackets

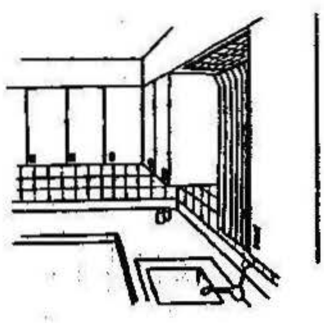
High wall brackets provide both up and down light for general room lighting. Used on interior walls to balance window valance both architecturally and in lighting distribution. Mounting height determined by window or door height.





(e) Lighted Low Wall Brackets

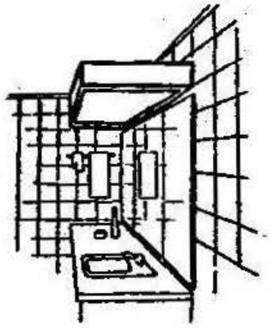
Low brackets are used for special wall emphasis or for lighting specific tasks such as sink, range, reading in bed, etc. Mounting height is determined by eye height of users, from both seated and standing positions. Length should relate to nearby furniture groupings and room scale.



(f) Lighted Soffits

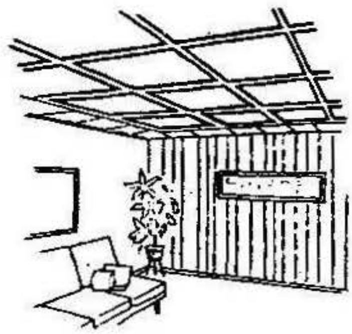
Soffits over work rease are designed to provide higher level of light directly below. Usually they are easily installed in furred-down area over sink in kitchen. Also are excellent for niches over sofas, pianos, built-in desks, etc.

Bath or dressing room soffits are designed to light user's face. They are almost always used with large mirrors and counter-top lavatories. Length usually tied to size of mirror. Add luxury touch with attractively decorated bottom diffuser.



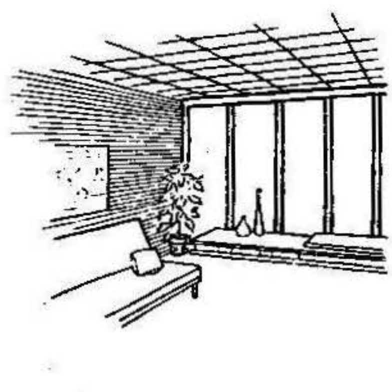
(g) Lighted Canopies

The canopy overhang is most applicable to bath or dressing room. It provides excellent general room illumination as well as light to the user's face.



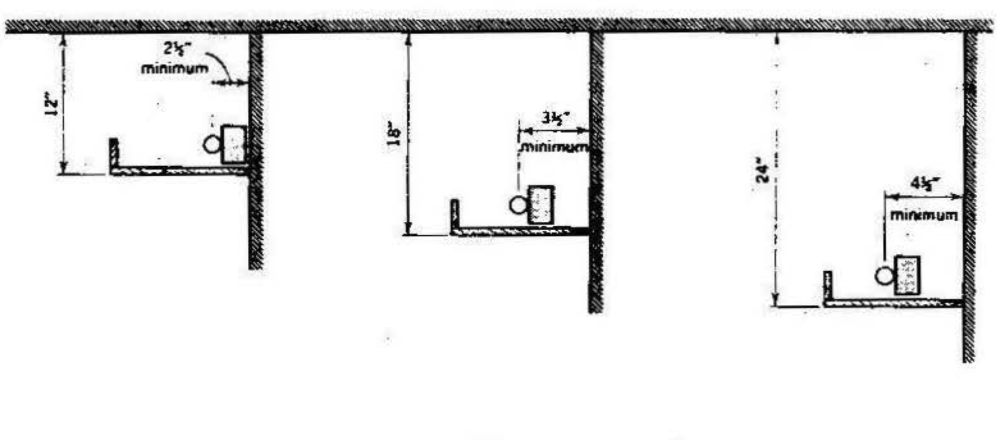
(h) Luminous Ceilings

Totally luminous ceilings provide skylight effect very suitable for interior rooms or utility spaces, such as kitchens, baths, laundries. With attractive diffuser patterns, more decorative supports, and color accents they become acceptable for many other living spaces such as family rooms, dens, etc. Dimming controls desirable.

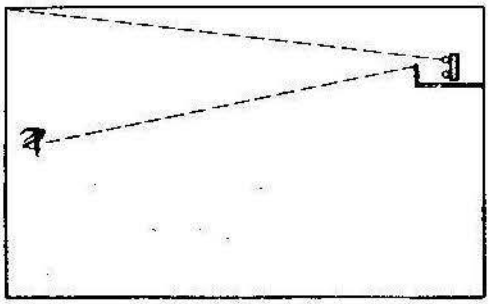


(j) Luminous Wall Panels

Luminous wall panels create pleasant vistas; are comfortable background for seeing tasks; add luxury touch in dining areas, family rooms and as room dividers. Wide variety of decorative materials available for diffusing covers.



Using fluorescent tubes, it is possible to avoid dark spots between lamps by placing lamps at a slight angle rather than end-to-end, thus enabling end to overlap. Reflectors, when used, should be aimed 15 ° to 25 ° above the horizontal and field-adjusted for best ceiling coverage. When using double strips they should be stacked vertically as shown in figure (m). Coefficients for double-lamp installation rarely exceed 0.75 times the single-lamp coefficient. Interiors of cove surfaces should be painted with a high-reflectance white paint with diffuse (flat) rather than specular (gloss) finish.



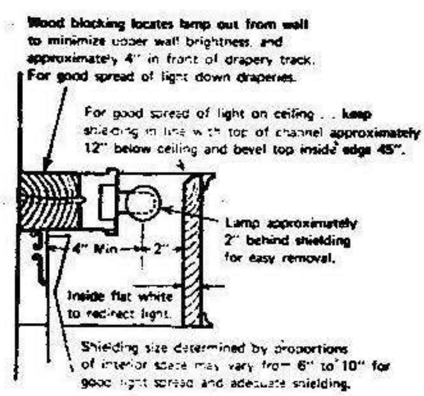
Proper cove proportions: Height of front lip of cove should shield cove from the eye yet expose entire ceiling to the lamp. Orientation of fluorescent strip as shown is preferable to upright arrangement.

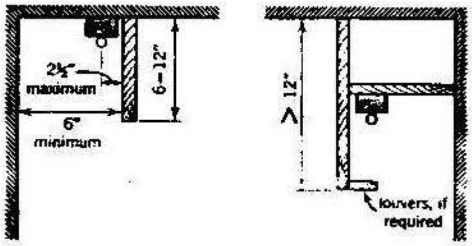
The figures below five dimensions of typical wall-washing cornices and valance. Reflectors, though not required, increase the efficiency of the installation. As in the case of coves, finish of the valance interior should be flat white of approximately 30 to 40% RF. Incandescent fixtures may also be effectively employed in architectural lighting.

Typical Valance

This "typical" dimensional drawing applies only to commonly encountered window valance situations. Obviously, other window treatments could necessitate modifications in these critical dimensions; i.e., vertical blinds, double track situations, curved bay windows, etc.

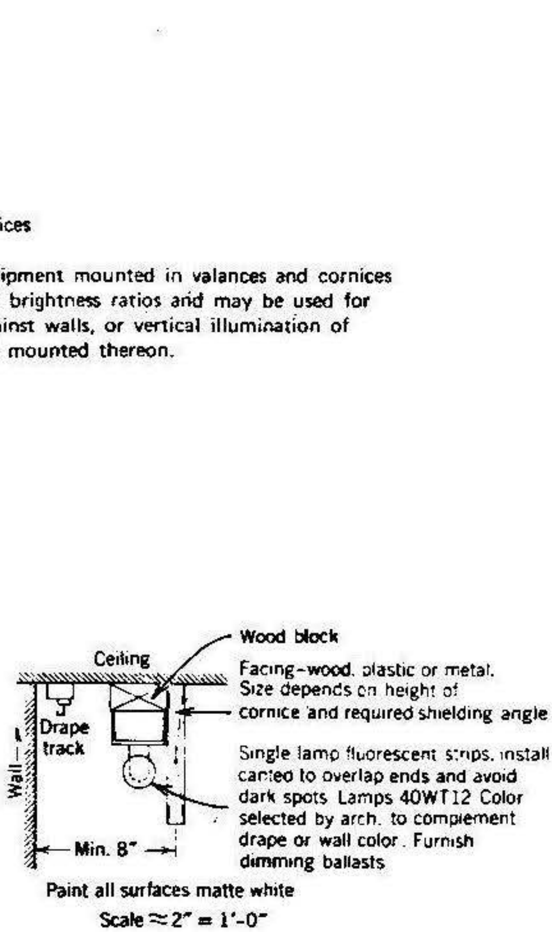
The same "job-tailored" variations can occur in the design of any type of structural lighting device. Therefore no other dimensional drawings have been included here.





(n) Typical Cornices

Wall washing equipment mounted in valances and cornices provide improved brightness ratios and may be used for lighting desks against walls, or vertical illumination of walls and objects mounted thereon.



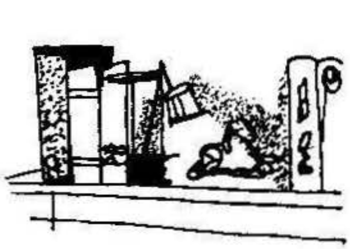
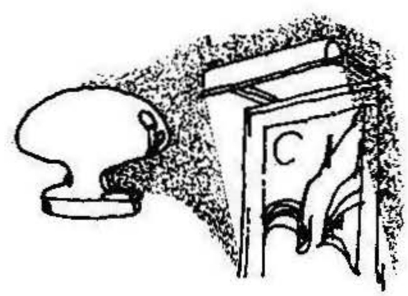
Although not always considered as an architectural element, sections of luminous ceiling are frequently employed in kitchens to some advantage. The difficulty lies in the lack of sufficient ceiling height. Lamp spacing should not exceed 1.5 times the cavity depth, for uniformity. An illusion of ceiling height may be obtained by blurring the ceiling-wall joint with light via a valance illuminating a light color joint.

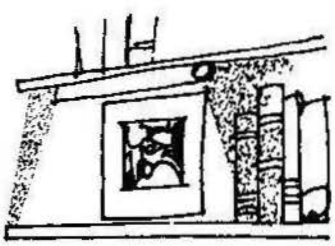
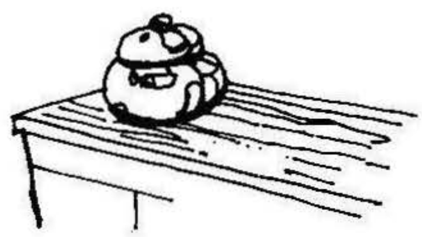
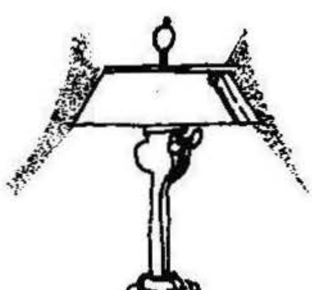
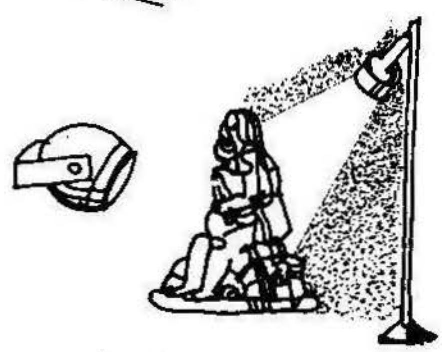
Portable Lighting

Add drama and individuality to your rooms. Highlight artwork, and treasured possessions, create intriguing shadow patterns, or introduce a glowing decorative touch with plug-in units that are easy to install or move around, but give a lot of impact.

Decorative Lamps

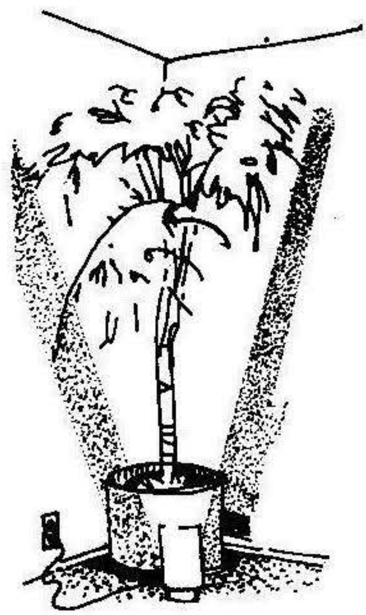
Since accent lighting is meant to personalise a room and not for functional light to see by, you can indulge in whimsy, fashion or sentiment. Whether traditional styles, converted objects or luminous contemporary forms, truck small lamps in book shelves or on a hutch, or use larger lamps on buffet or occasional tables. Use low wattage bulbs-especially if there are luminous parts-to avoid glare.

Floor Cans

Under plants or tucked in corners give dramatic uplight, creating shadow patterns on the upper walls and ceiling. Use 50 or 75 W reflector bulbs.



Picture Lights

Picture lights that mount on the picture frame or on the wall highlight treasured paintings, prints, or photos, create interesting vertical brightness in a room. Use T-bulbs or Hi-lights.

Portable Spots

Free standing, wall mounted or attached to a track, have a directional beam creating sparkling highlight and deep shadow, especially good on small sculpture and flowering arrangements. Use 25, 30 or 50 watt spots or special narrow spot reflector bulbs.

General Lighting

General lighting is background light in a space that reduces bright contrasts between task lights and lets you move about easily. In living areas, it is a soft fill-in light provided by reflected light from open top lamps wall lighting and ceiling or wall fixtures.

Living Rooms, Dens, Family Rooms and **Recreation Rooms** accomodate a variety of activities which require lighting flexibility. Dimmer control of general lighting lets you change the atmosphere of a room to suit your mood easily and quickly.

Diffusing ceiling fixtures in **Kitchen** and **Laundry** provide light to see into cabinets and drawers for safe, speedy working.

General lighting is needed in **Bedrooms** for housekeeping chores, care of invalides of children and for seeing into drawers and shallow closets.

Halls, Foyer and **Stairs** need overall light for safe passage.

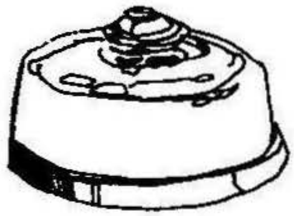
Each space has its own aesthetic and functional requirements. Select the most appropriate technique listed here for your home.

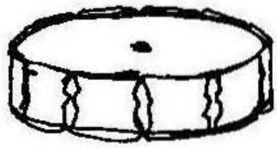
Switches, if entrances to a room are more than 10 feet (3.00m.) apart, there should be a switch at each one. Conveniently located switches remind people to turn off lights when not in use.

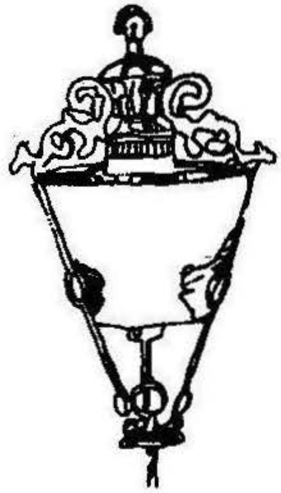
GENERAL LIGHTING RECOMMENDED FOR LIVING AREAS

Room Size	Fixtures Suspended or ceiling mount
Small under 150 sq. ft.	Inc: 3 to 5 socket fixture, total 150–200W or Fluor: 40–60W
Average 185–250 sq. ft.	Inc: 4 to 6 socket fixture, total 200 to 300W or Fluor: 60–80W
Large over 250 sq. ft.	Inc: 1 watt per sq. ft., 1 unit per 125 sq. ft. or Fluor: 13 watt per sq. ft.

Wall Lighting Reflector Incandescent or linear Fluorescent	Recessed Units with enclosed bottom minimum 12" wide
Inc: four 50W reflector bulbs or Fluor: 60–80W	Inc: four 75W or Fluor: 80W
Inc: 5 to 8 75W reflector bulbs or Fluor: 120–160W	Inc: four 100W or Fluor: 120W
Inc: one 75W reflector bulb for each 25 sq. ft. or Fluor: 160W	Inc: one 100W or 150W per 40–50 sq. ft. or Fluor: 160 to 200W







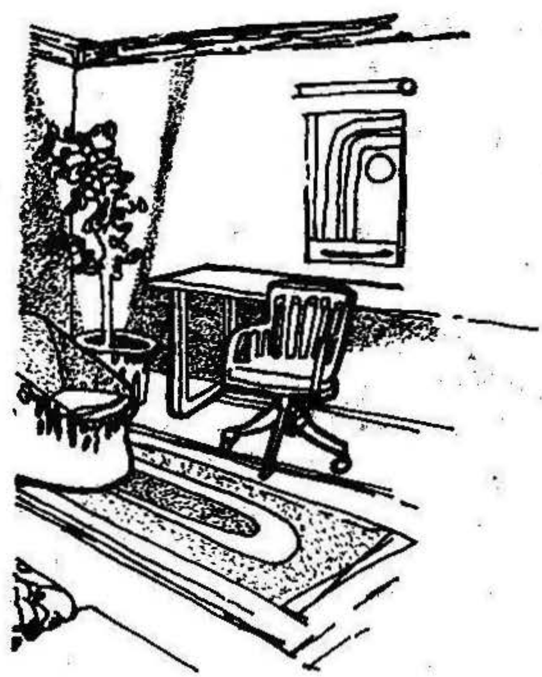
Incandescent Wall Lighting

Fixtures may be recessed, ceiling mounted or attached to track. When lighting a wall behind a seating group, excercise care so people seated there do not see the brightness of the bulb or interior of the fixture.

Open Reflector Downlights

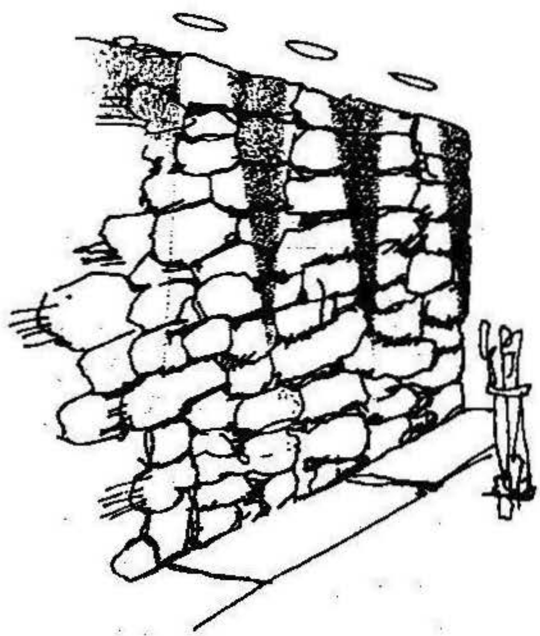
Either recessed, surface or track mounted, create a scallop pattern on the wall and emphasize texture such as brick, stone or a rubby wall covering. Space non-adjustable fixtures 8 to 16 inches (0.20 to 0.40 M) from wall and 18 to 30 inches (0.45 to 0.75 M) apart. The light pattern falls lower on the wall the faster away the fixture is and the scallops are deeper the farther apart the units are.

Mount track 24 to 28 inches from wall (0.60 to 0.70 M).



Wall Washers

Wall washers light a wall evenly from top to bottom eliminating scallops and de-emphasising texture. Especially suitable for lighting large artwork and picture groupings. Generally, the distance between fixtures should be the same as the distance between the fixture and the wall, ex: 2 feet out and 2 feet apart or 3 feet out and 3 feet apart. Not suitable for us over a sofa against a wall.



Through Lighting

This consists of strips of small reflector bulbs, usually track mounted, concealed behind a baffle or board, or recessed in the ceiling. It produces a grazing light that dramatizes texture. Shielding should be 12 inches (0.30 M) from wall, at least 9 inches (0.23 M) deep and have a 3 inches (0.076) return. Space 50 W reflector bulbs 12 inches (0.30 M) apart, 75 W R 30's at 18 inches (0.45) apart and 75 or 100 W standard bulbs in special reflectors at 24 inches (0.60 M) apart.

Wall Lighting

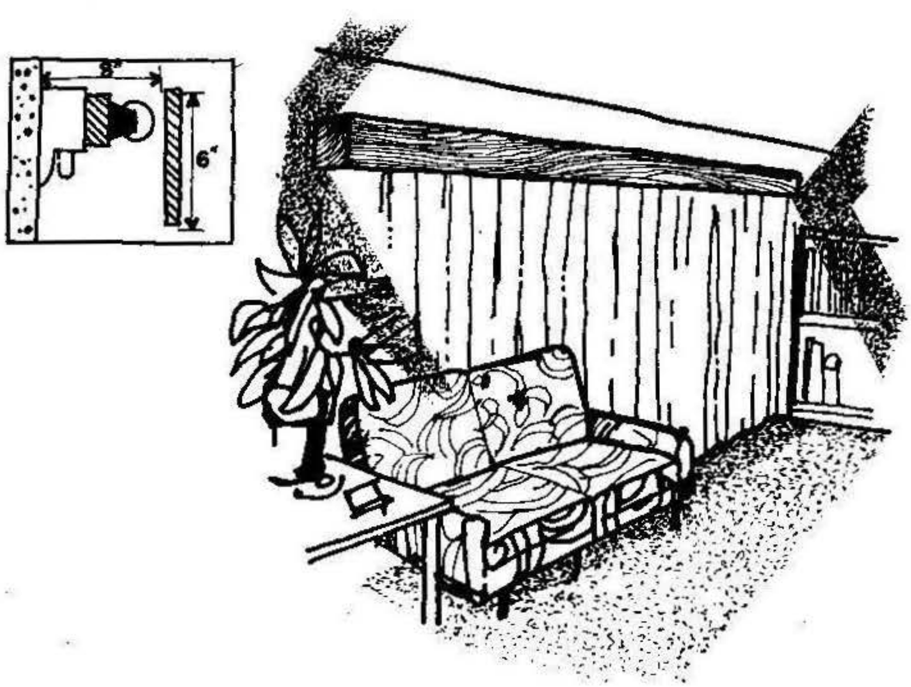
Lighted walls expand space visually, making rooms seem larger. Whether you choose to emphasize the texture of a wall or bathe it in a soft light, wall lighting provides a comfortable background for task and accent lighting and enhances any decor.

Fluorescent Wall Lighting

Energy wise fluorescent strips concealed behind a shielding board produce a soft diffuse, light, suitable in living and dining areas, bedrooms, family rooms and dens. Use soft white home fluorescent for a flattering light that blends well with incandescent light.

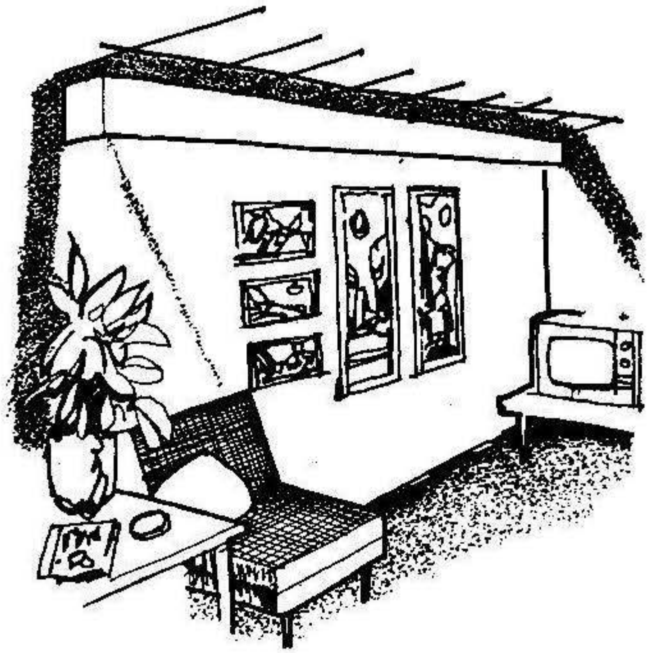
Cornice Lighting

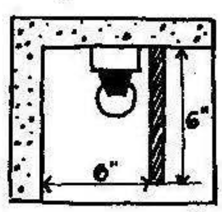
This provides downlighting only. Used to light draperies, walls or murals, it creates a sense of intimacy and is equally at home in traditional or contemporary, formal or informal interiors.



Valance Lighting

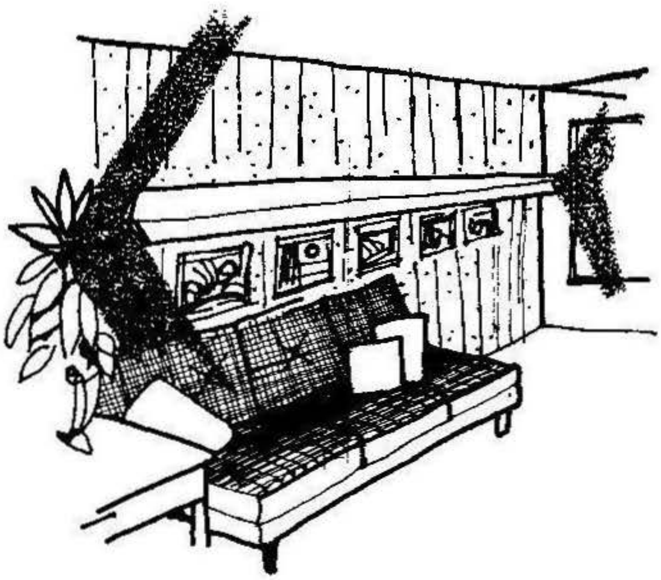
Custom or ready made, used over draperies, provides both upward and downward light, bathing both the ceiling and draperies in soft illumination. Informal in character, it can restore daytime lighting balance to a window wall at night.

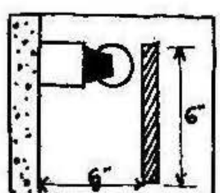




Valance Brackets

Like valances, provide both upward and downward light on walls and ceiling. Available in ready-made units for use singly or in runs. When mounted low on the wall, they can also provide task lighting; when installed over sliding door, closets, they give general room illumination as well as lighting the closet when open. Informal in Character.





Recessed Lighting

Recessed fixtures concealed above the ceiling give downward light only. Recessed incandescent is especially good for wall lighting and accent light while recessed fluorescent is better for general and task lighting.

Shielding

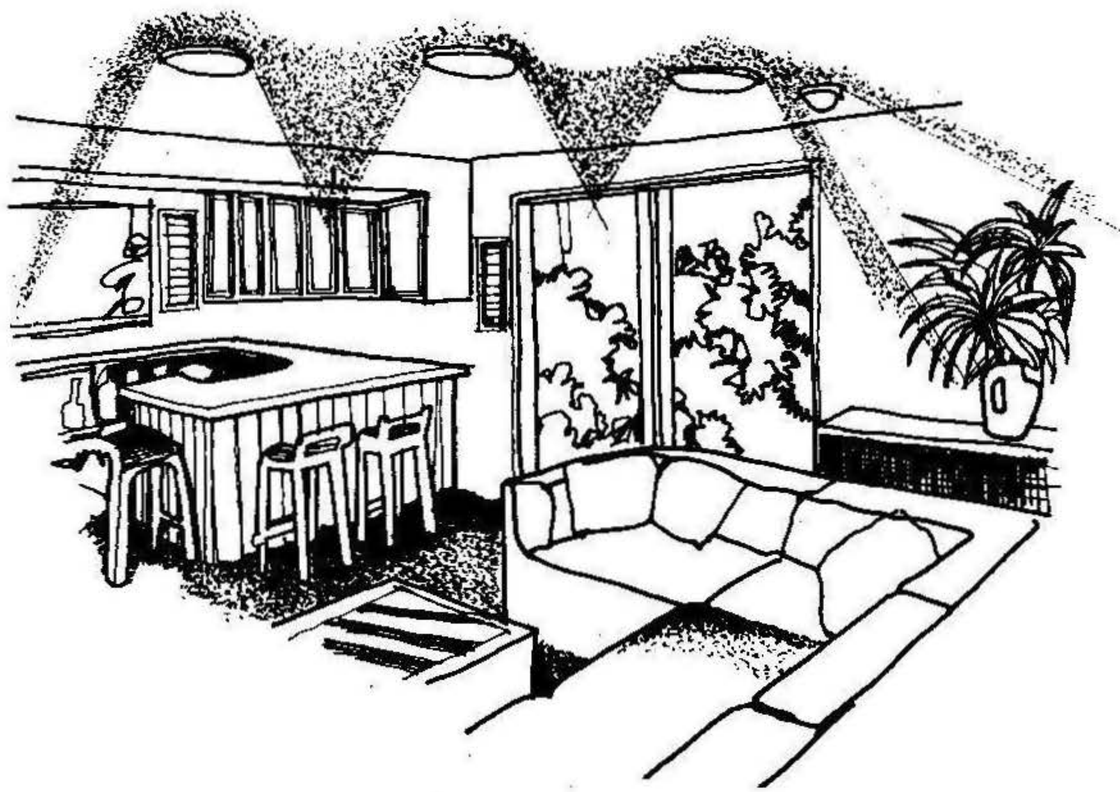
Deep recessed cans need baffles, louvers or reflector cones to control fixture brightness. Shallow fixtures, 4½ inches to 6 inches, (0.115 to 0.152 M), require lenses, louvers or diffusers across the bottom, none of which should project below the ceiling. For best effect use floor covering that is neutral in colour and has a fairly high reflectance. Use one floodlight for every 25 sq. ft. approx. (2.30 sq. m) of floor area for general area lighting. Avoid placing units directly above seating locations.

Light from recessed INCANDESCENT fixtures can be controlled and redirected by reflectors and lenses. Other than open downlights which usually take a reflector bulb, some frequently used types are

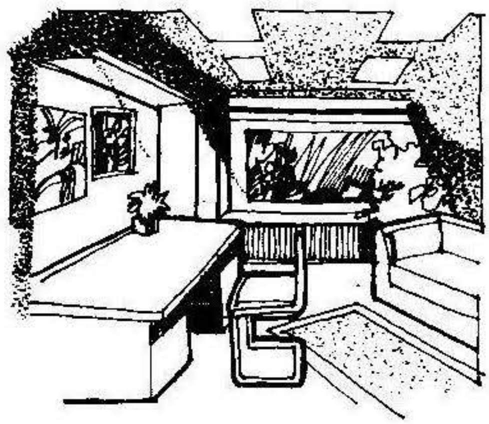
a. An **eyeball** is an adjustable spherical fixture that projects below the ceiling. Uses a reflector bulb.

b. A **wall washer** eliminates scallops, gives even light from top to bottom on a wall. Uses 100 W or 75 or 150 W reflector flood.

c. A **pinpoint spot** has an inconspicuos 1 inch diameter opening in a faceplate that covers the fixture. Best to use a spot, or the bulb recommended by the manufacturer.



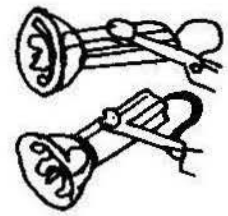
Recessed FLUORESCENT gives a wide spread of diffuse light suitable for task and general lighting especially in areas with low ceilings. Low brightness lenses or louvers provide a more comfortable environment than diffusers. Use Soft White home fluorescent to blend well with incandescent lighting. Good for bathroom, kitchen, laundry, recreation room.



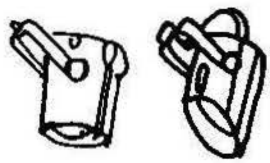
Tracklighting

Tracklighting offers versatility and ease of installation. The track is a metal channel containing one or more electrical circuits. A wide variety of fixtures may be attached anywhere along its length and just as easily detached and moved elsewhere. Track can be mounted on the ceiling or wall or suspended, arranged in lines, T's, squares or other patterns to suit your needs. It may be mounted on an outlet box or fed by a cord and plug. Adapters for single outlet box mounting and for weighted bases are available.

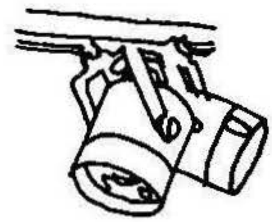
Track attachments can be simple lampholders or one of many modifications of a can, producing directional light and usually adjustable. Adapters are available for attaching chandeliers, pendants and fluorescent fixtures to the track. Commonly used attachments include:



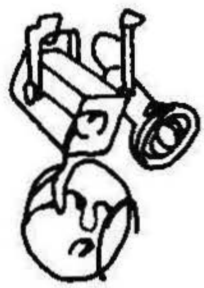
a. **Open Downlights** for accent, task and wall lighting. Gives directional light good for highlight and shadow.



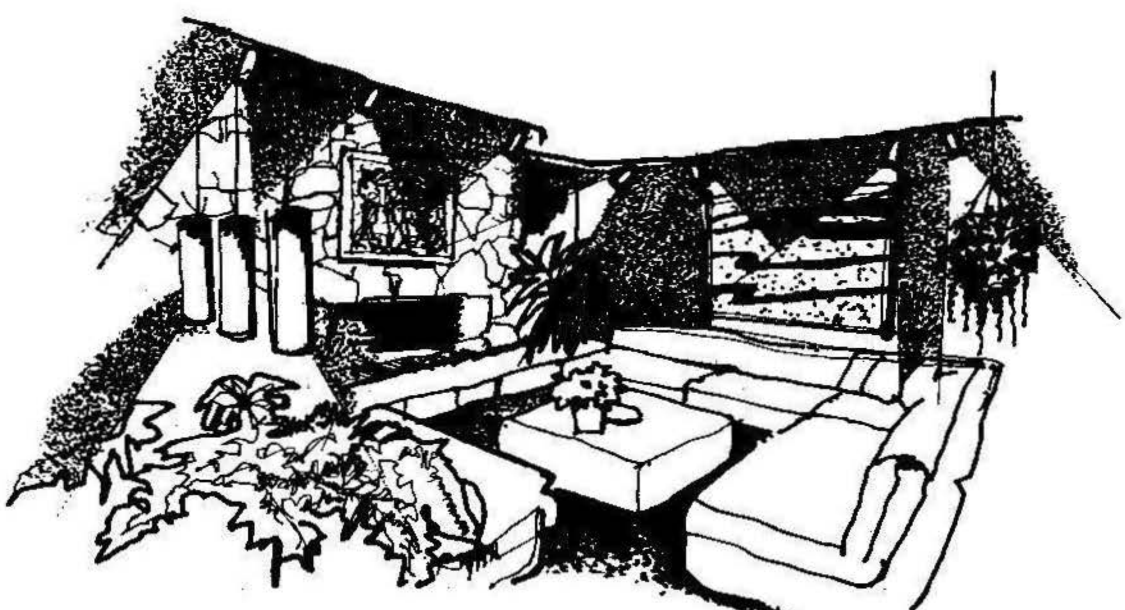
b. **Lampholder** for decorative accent or general lighting with exposed globe bulbs, 25 to 100 W.



c. **Wall Washers** bathe a wall evenly with light. Uses 100 A or 75 or 150 W reflector flood.



d. **Projector** or **Low Voltage Spots** provide well controlled beams of light for accent lighting. Use bulbs recommended by manufacturer.



Lighting for the Foyer, Hall and Stairs

Welcome guests, keynote decor and provide safe passage with well chosen fixtures. In sparsely furnished halls, they are an important decorative asset. General diffusing provide maximum lighting effect. Coordinate style with adjoining areas.

a) **Large Entrance Hall:** 75 to 150 square feet (7 to 13.50 sq. M). Use single shielded fixture, minimum 12 inches (0.30 M), or multiple arm with shades, minimum 18 inches (0.45 M) diameter, or wall fixtures.

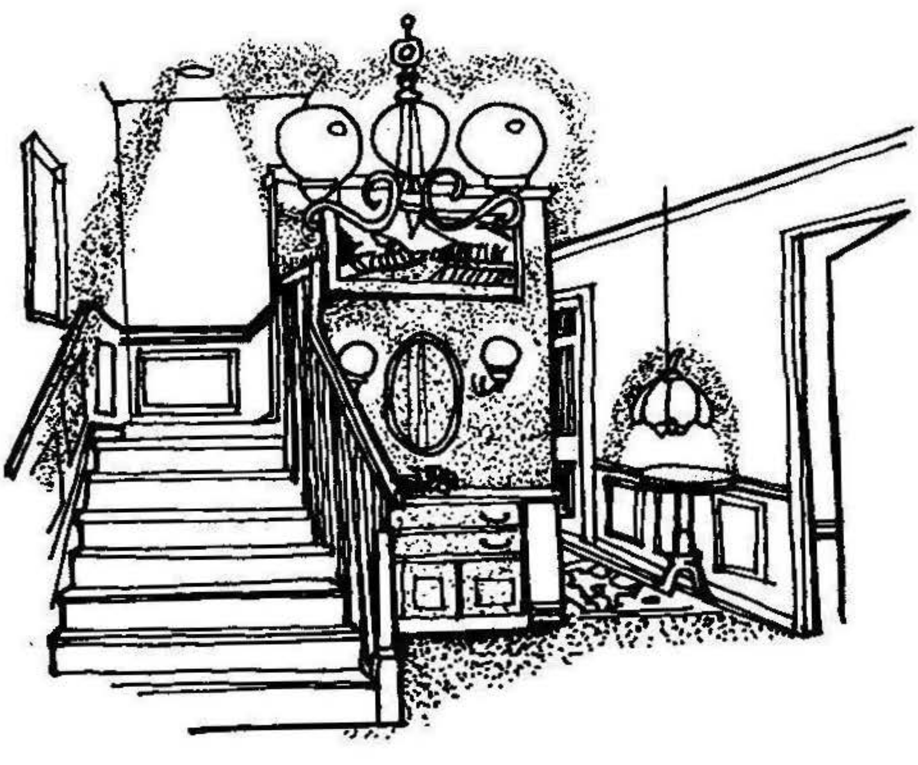
   Bulbs and Tubes: Fluorescent — 22 + 32 W or 40 W circline, two 36 inches 30 W or 48 inches 40 W tubes. (0.90 to 1.20 M) Incandescent — one 150, or three 60 W.

b) **Small Hall or Vestibule:** 20 to 75 square feet (1.80 to 7 sq.m). Use single shielded fixture, minimum 8 inches diameter (0.20 M), or multiple arm with 10 to 12 inch spread, or wall fixture.

   Bulbs and Tubes: Fluorescent — circlite 60, 22 or 32 W circline, 36 inches (o.90) 30 W or 48 inches (1.20 M) 40 W.
   Incandescent — one 100 W, two 60 or three 40 W

c) **Hallway:** repeat vestibule fixture every 10 feet (3.00 M). Use fluorescent fixtures in windowless halls that need light all day — saves energy, reduces bulb replacement.

d) **Stairs:** Locate hall fixtures near both top and bottom of stairs. Shielding across the top is needed if you can see into a fixture when descending the stairs. If there is a stair landing, mount matching fixture over it or use a fluorescent wall bracket.



e) **Closets:** for walls — in areas over 9 square feet (0.90 M): Fluorescent — circlite 60 or circlite 100, 22 or 32 W circline; Incandescent — 60 or 75 W (surface fixture), 100 A or 75 R 30 (recessed unit).

If fixture is less than 18 inches (0.45 M) from shelf, it must be recessed.

Accent Lighting

Personalize your rooms and show of prized possessions with pools of brightness that draw the eye. Controlled beams of light make objects stand out from their background, inviting attention. Accent light is usually directional in character and should be used with general lighting for comfortable viewing. Most accent lights may be recessed or track mounted.

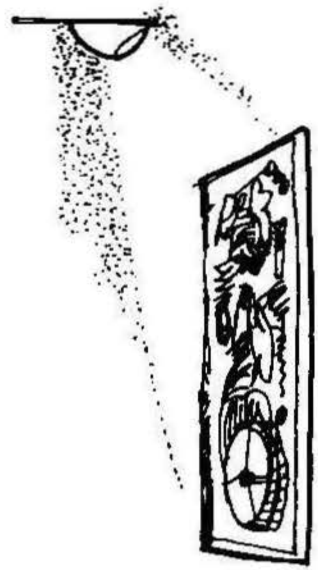
Open Reflectors Fiber works, paintings, prints or photos benefit from directional light. Aim adjustable units at a 30° angle to center of work or approximately 5 feet (1.50M) above the floor to avoid reflected glare — particularly important with glass covered works. Use reflector spot for narrow beam of light or a flood for softer wider beam with about ½ the intensity of a spot of the same wattage.

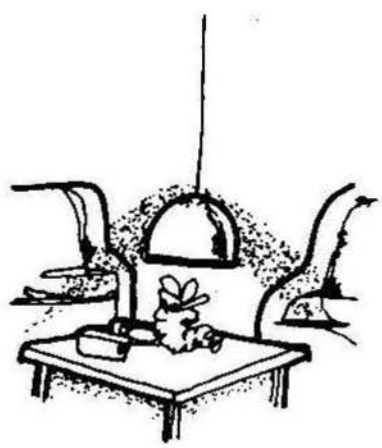
Low Voltage or Projector Spots can provide a very narrow beam for a small area or a long throw. Good for small sculpture. Always aim at an angle. For good modeling effect use one unit on either side for cross lighting. Light from straight ahead flattens objects.

Framing Projectors eliminate spill light around a picture or table top, shape a beam to fit an object precisely.

Pendant Downlights hung low over a cocktail table invite people to gather around. A series hung over a planter can enhance plant growth with Gro and Sho reflector bulbs as well as act as a room divider.

Built-in shelving and display cases benefit from open reflector downlights or shielded fluorescent tubes concealed in the top. Fluorescent tubes or "T" bulbs may also be concealed along the sides.





LIGHTING

CREATING A MOOD

Apart from its many functional applications, well planned lighting can contribute a great deal to the atmosphere in your home. The position and style of the lamps and fixtures determines the kind of light they give. Candle light and oil lamps have long been associated with a warm and cosy atmosphere, and you can create an almost identical mood with modern lighting using small spotlights or shaded lamps to make isolated pools of light around the room. The mood may be enhanced where a dark floor or ceiling absorbs the light rather than reflects it. If, on the other hand, you want to create a fresh, airy appearance, use reflected light from pale coloured ceilings and walls. Ideally, lighting should be as flexible as possible so that you can arrange it to suit the occasion; this cannot be achieved merely by fitting dimmer switches.

WELL BALANCED LIGHTING

When you plan your lighting, first consider the size and position of the windows and the amount of natural light they bring to the interior. Some areas may have poor illumination and will need subsidiary lighting during the daytime. The most efficient method of achieving the correct balance is with a light-sensitive switch: When the natural light level falls below a certain point, artificial light is automatically switched on. This is particularly useful in areas of potential hazard such as stairway, where light should be thrown on to the stairs, so that the edge of the tread is well defined. Ideally, the light source should be to one side so that your shadow does not obscure the stairs when your are going up or down. Always avoid sudden changes in light level.

PLANNING INSTALLATIONS

Plan your lighting first before you decorate or build any furniture into a room. Position outlets carefully, to give you as much flexibility as possible. Place lights switches within easy reach as you enter a room—a point to remember if you intent rehanging a door. Two way switches are very useful placed at the top and bottom of a staircase, or by the side of the bed. Bear in mind that light fixtures have to be cleaned and maintained, so if you need a light in a normally inaccessible area, consider installing a flush-fitting or a recessed light that will require less cleaning.

1. **Creating atmosphere**

   Create small pools of atmospheric light by strategically positioning lamps at a low level around the room. **(see illustration no. 1).**

2. **Reading Lights**

   Reading lights are provided in this bedroom, by positioning strip lights behind a batten running across the headboard. Provide a separate light and switch for each side of the bed so that one person can read without disturbing the other. **(see illustration no. 2).**

3. **Reflecting light and textures**

   Position your light fittings to make the most of textural surfaces in the room. Supplement low level lamps by using reflected light from the ceiling. **(see illus. no. 3).**

4. **Reinforcing natural light**

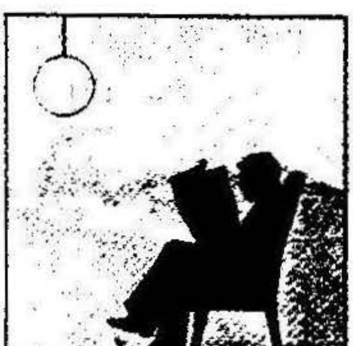
Directional spotlights reinforce natural light from a skylight, while at the same time picking out pictures hung on the wall.

A GOOD SOURCE OF LIGHT

Plan carefully to create an overall, harmonious effect that will at the same time satisfy individual activities. You should arrange your light sources so as to avoid throwing shadows into activity areas while reducing glare from a direct light source.

READING LIGHT

A centrally place ceiling light as in 1 is unsuitable for reading, since it casts shadows on the page. A better arrangement is shown in 2 where a lamp is positioned behind and to the side so that light is thrown on to the page. Another low-level light should be used to reduce contrast between the well-lit page and the darkened background.



1 Central light casts shadows

2 Reading lamp positioned behind

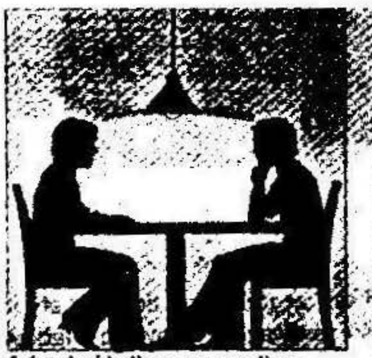
TELEVISION VIEWING

Low-level, indirect light adjacent to the set, 3, reduces eye strain.

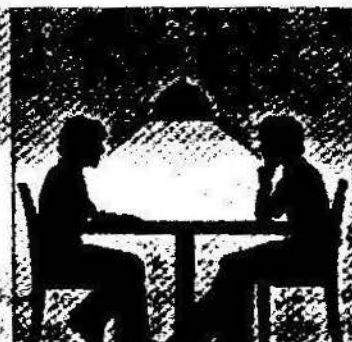
3 Indirect lighting near television

LIGHTING A DINING AREA

Avoid light fixtures in which the naked bulb is visible to diners as in 4. If possible, install a light with a wider shade that can be adjusted up and down thus preventing glare. Additional lighting may be necessary for long tables as in 6.



4 A naked bulb can annoy diners



5 Rise and fall fittings avoid dazzle

6 A long table needs two lamps

LAMPS FOR WRITING

Avoid light that throws your own shadow on to the page as 7. Much better is a concealed light as in 8, which causes less shadow by partially reflecting on the wall. An adjustable lamp such as in 9 provides the best illumination and combined with another room light will reduce eye strain.

7 A high lamp casts shadows

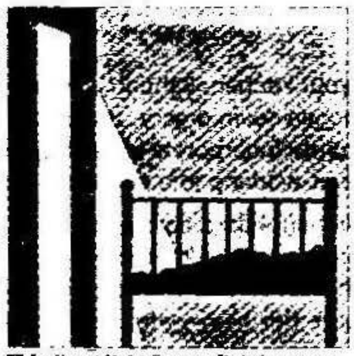
8 Concealed lamp gives better light

9 Use an adjustable lamp for typing

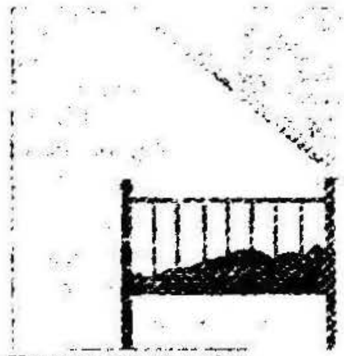
BEDROOM LIGHTING

A reading light should be positioned to one side of the bed, or behind it, as in 10, shaded to avoid glare. Indirect light in child's room can be provided from an adjoining area 11, or a dimmer switch 12.

10 Position reading light behind bed



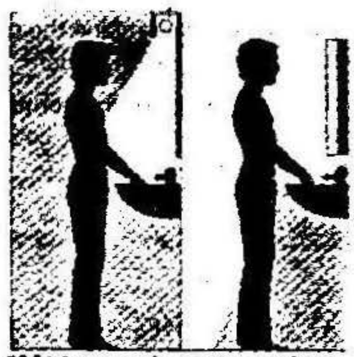
11 Indirect light from adjoining area



12 Install a dimmer switch

BATHROOM LIGHTING

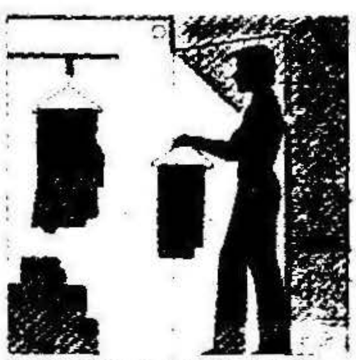
Position the light to shine on you—not the mirror, 13. Place the light either side of the mirror or around the perimeter and avoid lights which will reflect in it.



13 Light mirror from side, not above

LIGHTING CUPBOARDS AND SHELVES

Interior cupboard lights can be controlled by a switch operated by the opening and closing of the door. Use as concealed or shaded strip light, as 14. Position a light above shelves as in 15.



14 Illuminate cupboard interiors

15 Light shelves from above

SELECTING KITCHEN COMPONENTS

Of all the components in your kitchen, lighting is afford to skimp on. Not only can poor lighting make the cheeriest kitchen seem dreary. It can also promote fatigue and even cause accidents. A good rule of thumb; incorporate enough general, task, and accent lighting in your kitchen so that you're never working in a shadow.

You'll likely outfit your kitchen with a combination of incandescent and fluorescent bulbs, incandescent bulbs (or lamps, as they're known to the trade) are made in a wide range of wattages, but those in the 60- to 200-watt range are your best bets for a kitchen. Bulbs typically last from 750 hours (for high-wattage bulbs) to 2,500 hours (for low-wattage and "long life" bulbs).

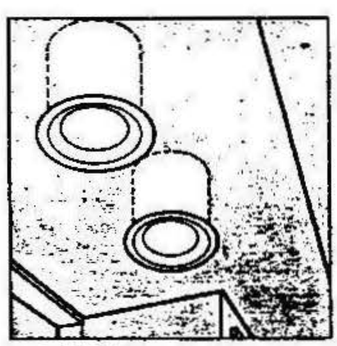
Fluorescent tubes give off between two and three times as much light per watt as incandescent bulbs, and are more economical to operate. Though the life-span of a fluorescent tube exceeds that of an incandescent bulb, it's shortened if the tube is frequently turned on and off. Choose fluorescents for your kitchen carefully; "warm white" tubes (rather than the harsher "cool white" type) are more flattened to food.

To light an average-size 10 x 12-foot kitchen, you'll need about 250 watts of incandescent light, or 90 watts of fluorescent light. To combine the two, allow about 2 watts of incandescent or 3/4 watt of fluorescent light for every square foot of kitchen space.

Of course, your particular kitchen lighting requirements depend on a number of things—ceiling height, ceiling color, and your overall kitchen color scheme. Light, pale colors reflect nearly as much light as deep, dark colors.

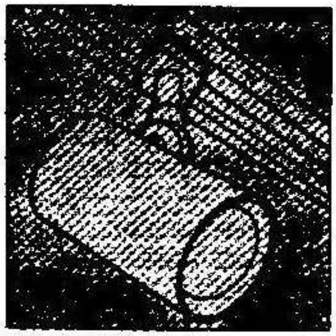
YOUR KITCHEN LIGHTING OPTIONS

Since most kitchen chores take place at the sink, you'll want it especially well-lighted. If your sink is under a window, opt for a recessed downlight that provides at least 150 watts of incandescent illumination, or fluorescents behind a diffuser panel. For a sink that's under a cabinet or shelf, choose diffused fluorescent tubes, or soffit canister lights recessed in the soffit bulkhead or upper kitchen cabinets.



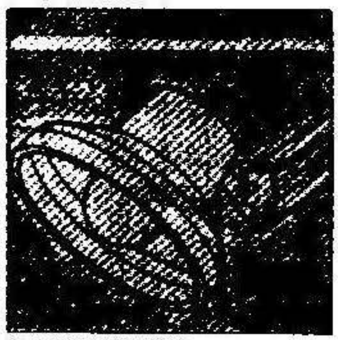
A. SOFFIT
CANISTER LIGHTS

Of all your kitchen lighting options, track lights offer the most versalility. Fixtures come in myriad styles, and give the look of built-in lighting without the installation hassle. Tracks mount on ceilings or walls, for task lighting at work centers or general kitchen illumination. For task lighting, fit track fixtures with spotlight bulbs; for general illumination, install more diffuse floodlight bulbs.



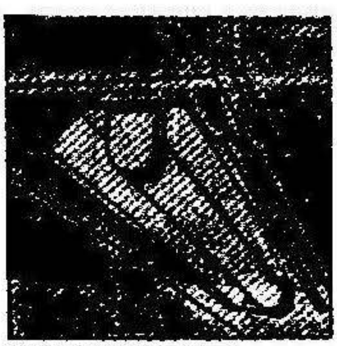
B. TRACK LIGHT

A desk light augments your general kitchen lighting at a kitchen office or planning center. An adjustable reading light fitted with a 50 to 75-watt incandescent bulb is adequate for all but extended reading.

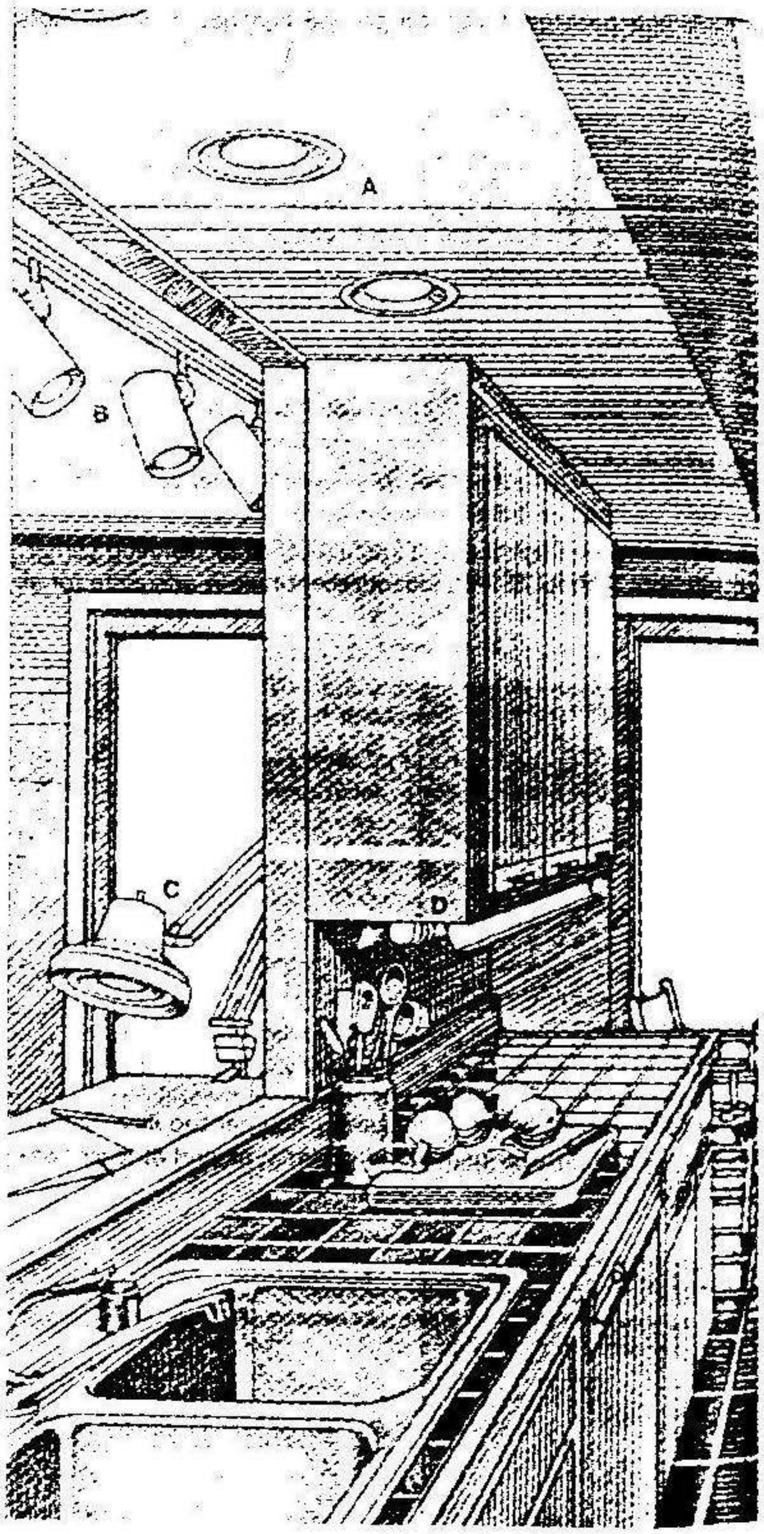


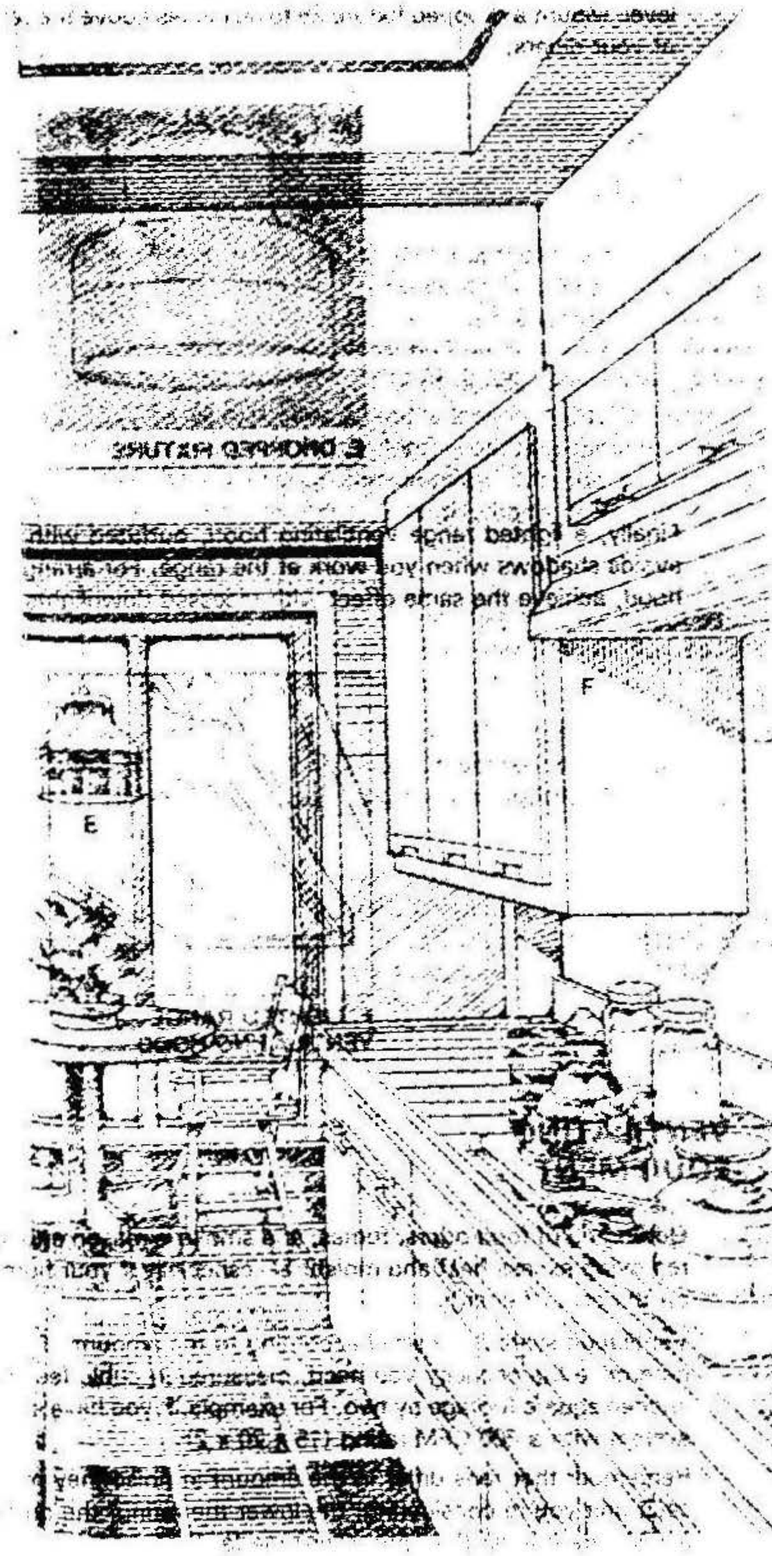
C. DESK LIGHT

Easy-to-install under-cabinet fluorescent lights are excellent counter-top illumination. Hide the tubes with a baffle, cornice, or diffuser panel, and let them extend at least two-thirds of the length of the counter.



D. UNDER-CABINET FLUORESCENT LIGHTS

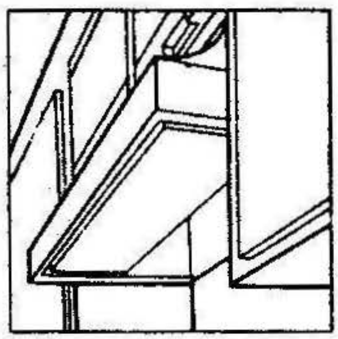

A
B
C
D


E
F

If you use a dropped fixture over your eating area, choose one scaled in size to complement your table, and in brightness to harmonize with the rest of your kitchen. Plan on minimum of 150 watts, but also use a dimmer switch or three-way bulb to vary the light level. Mount a dropped fixture 28 to 36 inches above the table so it doesn't obstruct the view of your diners.

E. DROPPED FIXTURE

Finally, a lighted range ventilating hood, outfitted with at least 60 watts of illumination, avoids shadows when you work at the range. For a range or cooktop not equipped with a hood, achieve the same effect with recessed downlights or soft canisters.



F. LIGHTED RANGE VENTILATING HOOD

VENTILATING EQUIPMENT

Getting rid of food odors, fumes, and smoke is reason enough to ventilate your kitchen. But removing excess heat and moisture—especially if your home is air conditioned—also saves on the cost of energy.

Ventilation system are sized according to the amount of air they'll move in one minute. To determine the capacity you need, measured in cubic feet per minute (CFM), multiply your kitchen square footage by two. For example, if you have a 15 x 20-foot kitchen, you'll need a system with a 600 CFM rating (15 x 20 x 2).

Remember that fans differ in the amount in noise they make. Check the "sone" rating on each unit you're considering; the lower the rating, the quieter the fan. Centrifugal blowers usually are quieter than propeller-type fans.

The type and placement of your range hood or fan ate just as important as the CFM rating in getting the most efficient ventilation. Here are your ventilation options.

EDUCATIONAL FACILITIES

Institutional and Educational Buildings

The lighting requirements for the various spaces in educational facilities are many and varied and, to a considerable extent, coincide with requirements for commercial (office) and institutional buildings. To that extent the remarks herein are applicable there also. Generally school buildings are constructed from capital budget funds and maintained from operating funds. The former is often based on sale of bonds, and makes a fixed amount available. The latter is financed through taxes and is always tight. Therefore, all equipment in public buildings must be extremely hardy, long-lived, punishment-proof, as maintenance-free as possible, and low in energy consumption. Maintenance in such buildings is generally poor and on a repair rather than preventive basis. With this in mind as overall criteria, the following remarks apply to lighting equipment.

(a) Use source with highest possible efficacy. Remember that daylight has the highest efficacy, followed by HPS (high-pressure sodium) lamps, fluorescent, and other HID (High-intensity Discharge) sources.

(b) Where specific color lamps are called for, such as deluxe white. The requirement should be permanently stencilled in large letters on the lighting fixture.

(c) Long-life sources should always be given preference because of lower maintenance. Thus corridor and stair lighting should be fluorescent. This is also important in locations where relamping is difficult as in high ceiling rooms such as gyms and assembly rooms. In such spaces, relamping should be possible by stick, and extended — life lamps are recommended, with preference to HID sources.

(d) In calculating levels, low figures for LLF (light loss factors) should be used to allow for aging of paints and dirt accumulation. Cleaning of lighting fixtures in schools is virtually unknown. A figure of 0. 5 to 0.6 is reasonable.

(e) Most schools are not air conditioned. The masking air noise being absent, careful control must be exercised on noise and vibration from ballasts, diffusers, etc. Ballasts noise increases with current rating, that is, 430-Ma very high output lamps. The latter two must therefore be used with caution, particularly in locations that amplify sounds, or where low NC obtains.

(f) Lighting equipment must be designed for an absolute minimum of maintenance. This means captive screws, rust-preventive plate parts, captive-hinged diffusers requiring only one man to maintain, ballasts replacement without demounting fixtures (plug-in ballasts are available). Non yellowing plastics, and high-quality finish and assembly levels of illumination are tabulated in the table.

	Recommended Minimum Footcandles
Industrial	
Airplane Manufacturing	
Parts manufacturing	
Drilling, riveting, and screw fastening	70
Final assembly	100
Airplane Hangars	
Repair service only	100
Assembly	
Rough easy seeing	30
Medium	100
Fine	500
Bakeries	
Mixing room	50
Oven room	30
Book Binding	
Cutting, punching, and stitching	70
Embossing and inspecting	200
Chemical Works	
Hand furnaces, boiling tanks, stationary driers, stationary and gravity crystallizers.	30
Clay Products and Cements	
Molding, pressing, cleaning, and trimming	30
Color and glazing—rough work	100
Cloth Products	
Cloth inspection	2000
Cutting	300
Sewing	500
Electrical Equipment Manufacturing	
Insulating: coil winding	100
Testing	100
Exterior Areas	
Entrances	
Active (pedestrian and/or conveyance)	5
Inactive (normally locked, infrequently used)	1
Building surrounds	1
Active shipping area	5
Storage areas—active	20
Storage areas—inactive	1
Loading and unloading platforms	20
Sheet Metal Works	
Miscellaneous machines, ordinary bench work	50
Presses, shears, stamps, spinning, me-	
Garages—Automobile and Truck	
Service garages	
Repairs	100
Active traffic areas	20
Parking garages	
Entrance	50
Traffic lanes	10
Storage	5
Inspection	
Ordinary	50
Difficult	100
Highly difficult	200
Most difficult	1000
Laundries	
Washing	30
Flatwork ironing, weighing, listing, and marking	50
Machine and press finishing, sorting	70
Leather Manufacturing	
Cleaning, tanning, and stretching, vats	30
Finishing and scarfing	100
Locker Rooms	20
Machine Shops	
Rough bench and machine work	50
Medium bench and machine work	100
Fine bench and machine work, fine automatic machines	500
Materials Handling	
Wrapping, packing, labeling	50
Picking stock, classifying	30
Loading, trucking	20
Inside truck bodies and freight cars	10
Paint Shops	
Dipping, simple spraying firing	50
Fine hand painting and finishing	100
Polishing and Burnishing	100
Printing Industries	
Printing plants	
Color inspection and appraisal	200
Composition	100
Presses	70
Proof reading	150
Receiving and Shipping (see Materials Handling)	
Exhibitions	30
Social activities	5
Banks (see also Offices)	
Lobby	50

	Recommended Minimum Footcandles
dium bench work	50
Punches	50
Stairways, Corridors, and Other Service Areas	20
Storage Rooms or Warehouses	
Inactive	5
Active	
Rough bulky	10
Fine	50
Testing	
General	50
Extra fine instruments, scales, etc.	200
Toilets and Washrooms	30
Upholstering—Automobile, Coach, Furniture	100
Watch and Jewelry Manufacturing	500
Warehouse (see Storage)	
Welding	
General illumination	50
Precision manual arc welding	1000
Woodworking	
Rough sawing and bench work	30
Sizing, planing, rough sanding, medium quality machine and bench work, glueing, veneering, cooperage	50
Fine bench and machine work, fine sanding, and finishing	100

Stores, Offices, and Institutions

	Recommended Minimum Footcandles
Art Galleries	
General	30
On paintings (supplementary)	30
Dark paintings with fine detail may require two or three times as much illumination.	
On statuary	100
In some cases, much more illumination is necessary to reveal the beauty of statuary.	
Auditoriums	
Assembly only	15
General	10
Corridors, elevators, and stairs	20
Entrance foyer	30
Linen room	
Sewing	100
General	20
Writing areas in lobby	70[a]
Teller's stations, posting, keypunch	150[a]
Barber and Beauty Shops	100
Churches & Synagogues	
Altar, arc	100
Pews	15
Pulpit (supplementary)	50
Club Reading Rooms	30
Courtrooms	
Seating area	30
Court activity area	70[a]
Hospitals	
Autopsy	
General	100
Supplementary	1000
Corridors	20
Emergency Rooms	
General	100
Local	2000
Examination and Treatment Rooms	
General	50
Examining table	100
Laboratories	
General	50
Closework	100
Patients' Rooms	
General	20
Supplementary for reading	30
Supplementary for examination	100
Recovery Rooms	30
Surgery	
General	200
Supplementary on table	2500
Toilets	20
Waiting Rooms	20
Hotels and Motels	
Bars and cocktail lounges (see Restaurants)	
Bathrooms	
General	10
Mirror	30
Bedrooms	
Reading (books, magazines, newspapers)	30
Subdued environment	15
Quick service type	
Bright surroundings	100
Normal surroundings	50

NOTE: Footcandle levels in dining areas are highly variable. Variations

	Recommended Minimum Footcandles
Lobby	
General lighting	10
Reading and working areas	30
Power Plant	
Boiler room	10
Equipment room	20
Storerooms	10
Libraries	
Reading rooms and carrells	70[a]
Stacks	30
Book repair and binding	70
Check-in and check-out, catalogs,	70[a]
Card files	100[a]
Offices	
General	
Cartography, designing, detailed drafting	200[a]
Accounting, auditing, tabulating, bookkeeping, business machine operation	150[a]
Regular Office Work	
Good copy	70[a]
Regular office work—reading, transcribing, active filling, mail sorting, etc., fair-quality copy	100[a]
Corridors, elevators, escalators, stairways	20
(Or, not less than ⅕ the level in adjacent areas.)	
Post Offices	
Lobby, on tables	30
Sorting, mailing, etc.	100
Storage	20
Corridors and stairways	20
Restaurants	
Dining Areas	
Cashier	50
Intimate type	
Light environment	10
Subdued environment	3
Leisure type	
Light environment	30
Theaters	
Auditoriums	
During intermission	5
During performance or presentation	0.1
Foyer	5
Entrance lobby	20

Residential (see Table 000 p. 000)

Outdoor Floodlighting

Building

depend on such factors as time of day, desired atmosphere, individuality, and attractiveness.

	Recommended Minimum Footcandles
Food Displays—twice the general levels but not under	50
Kitchen—commercial, hospital, hotel	
Inspection, checking, and pricing	70
Other areas	30
Schools	
Tasks	
Reading printed material	30[a]
Reading pencil writing	70[a]
Reading spirit duplicated material	
Good copy	30[a]
Poor copy	100[a]
Classrooms	
Chalkboards (supplementary illumination)	150
Drafting rooms	100[a]
Laboratories	100
Lecture rooms	
General	70[a]
Special exhibits and demonstrations	150
Lipreading classes	150
Shops	100
Sewing rooms	150
Sightsaving classes	150[a]
Study halls	70[a]
Corridors and stairs	20
Stores	
Store interiors	
Circulation areas	30
Merchandising areas	
Service stores	100
Self-service stores	200
Showcases and wall cases	
Service stores	200
Self-service stores	500
Feature displays	
Service stores	500
Self-service stores	1000
Stockrooms	30

Building Exteriors, and Monuments (Floodlighted)

	Surroundings Dark	Surroundings Bright
Light surfaces	5	15
Medium—dark surfaces	15	30
Dark surfaces	20	50

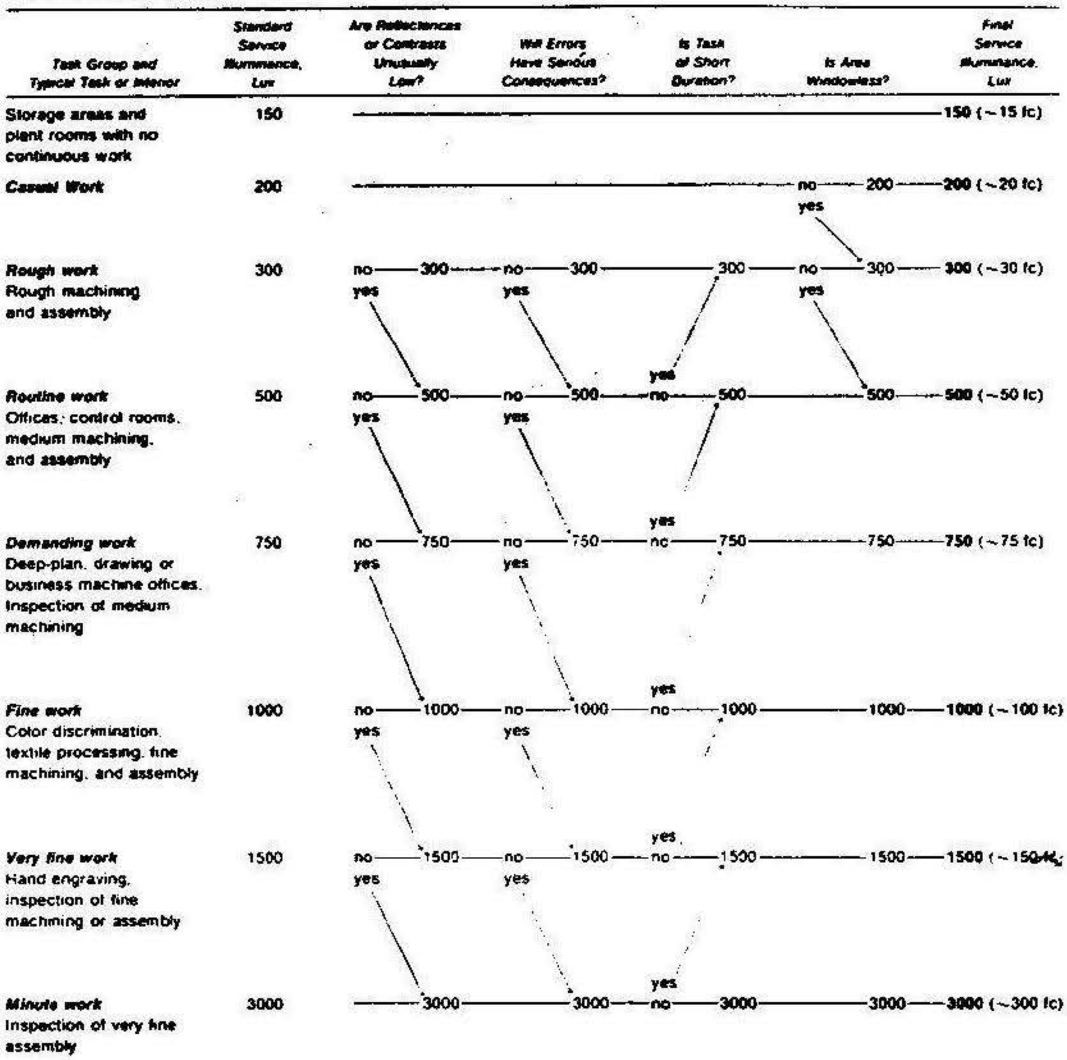
Flags 50

Parking Lots

Illumination Levels (Continued)

	Recommended Minimum Footcandles			Recommended Minimum Footcandles
Construction		10	Self-parking	1
Excavation		2	Attendant parking	2
Bulletins and Poster Panels			Shopping centers (customer attraction device)	5
	Surroundings			
	Dark	**Bright**		
Light surfaces	20	50		
Dark surfaces	50	100		

Table 18.5 ***Flowchart***



Art Rooms

The primary requirement here is for constant color daylight. Thus north windows and skylights are virtually indispensable. For artificial lighting, since color is so important, deluxe fluorescent tubes are recommended. General illumination should be augmented by user-adjustable supplementary lighting in the form of ceiling-mounted accent lights. If modeling is anticipated, spotlights for this purpose are required. For display of artwork, adjustable wall illumination is required. Ceiling track-mounted incandescent units are an excellent choice.

Art exhibition room, illustrating good and bad techniques. Upper wall fenestration is excellent for deep daylight penetration. Track lighting is ideal for display of art. The mixture of incandescent downlights for general lighting is excessive and an eyesore. Also, the positioning of the track lights can create both direct and reflected glare problems unless the sources are selected properly and ceiling height is above 9 ft.

Assembly Rooms, Auditoriums And Multipurpose Spaces

The varied activities in these rooms make flexible lighting imperative. For performances, low-level dimmed incandescent lighting is required. Here incandescent is the recommended source because of the lower cast of dimming and short burning periods. For assembly, this can be augmented by architectural elements along walls and drapes, and in the ceiling. For study, additional ceiling fluorescents or HID units can be switched on. The combinations are legion; the different usages are the critical consideration. See figures.

Schools frequently utilize spaces for multiple functions. This space, normally used as a dining area, doubles as an assembly room. The architecture did not lend itself to conventional fixtures. High-intensity, indirect tungsten-halogen units, in concrete beam junctures, provide sufficient light for both uses.

Institutional cafeteria illuminated by cove lighting in deep pyramidal coffers. Lighting is even, glare free, soft in quality, and pleasant, yet of sufficient intensity for use as a working meeting space. Photo by Stein.

The inaccessibility of high ceilings makes the use of very long-life sources such as HID (high-intensity discharge lamp) imperative. With incandescent, 130-V or extended-life lamps are recommended. An additional consideration is step lighting. These should be of very low brightness and mounted to the side of or in risers. Baffles and louvers must be provided in these units to cast light down only, to illuminate the tread, and particularly its leading edge. Acoustic considerations are acute because of the low NC criteria. Thus the generally noisy ballasts of HID sources should be located with care.

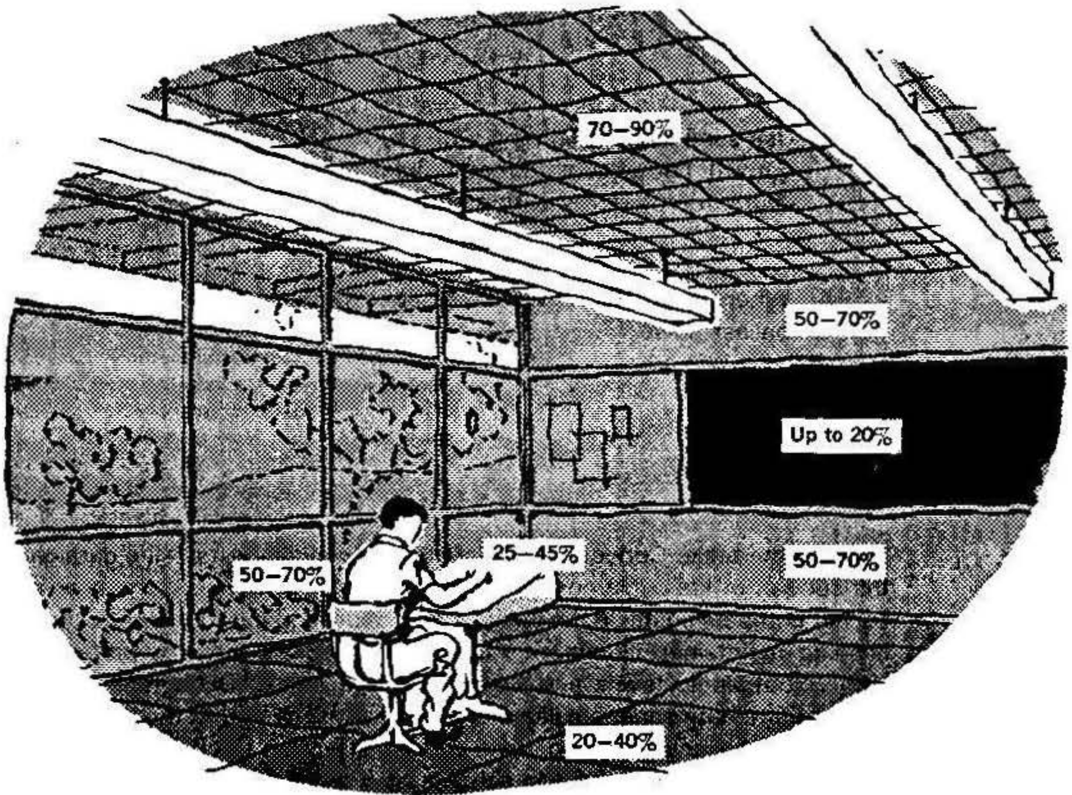
Gymnasium Lighting

Gyms present a situation similar to auditoriums in that they have widely varying usages. All fixtures should be sturdy and guarded. For gyms deluxe-white mercury. HPS (high-pressure sodium lamps), and metal halide are excellent choices for color, life, control, and efficiency. More than one level should be available by switching (see section on Mercury lamp (e) dimming chapter 13). For dance and assembly use, other fixtures can be lamped with long-life incandescent or Tungsten halogen, which provide good color for low-intensity lighting and also provide illumination during mercury startup or restart after an outage. Ratio of HID to incandescent can be between 4:1 and 5:1. All fixtures should be designed for relamping from the floor by means of stick or pole. Locker rooms should use guarded strip fluorescents. An interesting application of HID lighting in an indirect system is shown in the figure below. Recognition of a possible problem with dirt accumulation and relamping is necessary with such an arrangement.

This indoor tennis court uses 112 1000-watt metal-halide luminaires directed at the ceiling and reflecting shadow-free light of over 100 fc maintained on to the playing surface. Fixtures are mounted 20 ft above the floor. Sealed luminaires were chosen for both photometric performance and the low maintenance provided by their dustproof construction.

Classrooms

The essential room in the school is the classroom. Refer to the figure for recommended surface reflectances.



Recommended reflectances for surfaces and furnishings in the classroom. (Note control media used at windows to reduce exterior brightness so that they are in balance with interior brightness.)

The modern classroom utilizes extensive audiovisual teaching aids and therefore requires multiple aids and therefore requires multiple lighting levels. This is most economically accomplish by multiple switching and multilevel ballasts.

(a) **Energy Considerations and Sources.**
Use fluorescent, standard 430-ma lamps, cool and warm white, for direct and direct-indirect fixtures; 800-and 1500-ma lamps, same colors, for semi-indirect and indirect lighting. Incandescent sources should not be used. Daylight, to the maximum extent, is desirable. Lights adjacent to daylight sources should be separately switched.

(b) **Choice of Lighting System**
With proper design, adequate lighting can be provided with 2.5 w/sq.ft. Since ESI is so sensitive to viewing position and the recommended level is 70 fc ESI, the designer must be inherently familiar with the type of system, fixtures and arrangements that will yield the requisite high ESI without exceeding energy limitations. Some general guidelines are:

1. Run rows of fixtures front to back and, if possible, between rows of students.

2. Use high VCP units

3. Use semi-indirect lighting with HO or VHO (high output or very high output) fluorescent; direct-indirect, parabolic reflector, or batwing distribution fixtures with standard 430-ma lamps.

4. When using HO or VHO take special precautions against excessive ballast noise.

(c) Costs:

Refer to the table. Convert annual costs to life-cycle costs using data given in the section of life-cycle costing under Economic Analysis in the next pages. Do not compare costs on the basis of Pesos (dollars) per footcandle, that is, by dividing maintained illumination by cost, since this leads to preference for higher footcandle levels and higher wattage levels. Do compare life-cycle costs of alternate adequate illumination systems. Note that the analysis of the table does not include wiring costs and the effect on air conditioning. The latter, though rarely important in schools, is very important in office occupancies.

Standard Form for Calculation of Lighting System Costs on an Annual Owning Cost Basis

Lighting Cost Comparison

	Lighting Method #1	*Lighting Method #2*
Installation Data		
Type of installation (office, industrial, etc.)		
Luminaires per row		
Number of rows		
Total luminaires		
Lamps per luminaire		
Lamp type		
Lumens per lamp		
Watts per luminaire (including accessories)		
Hours per start		
Burning hours per year		
Group relamping interval or rated life		
Light loss factor		
Coefficient of utilization		
Footcandles maintained		
Capital Expenses		
Net cost per luminaire		
Installation labor and wiring cost per luminaire		

Cost per luminaire (luminaire plus labor and wiring)		
Total cost of luminaires		
Assumed years of luminaire life		
Total cost per year of life		
Interest on investment (per year)		
Taxes (per year)		
Insurance (per year)		
Total capital expense per year		
Operating and Maintenance Expenses		
Energy expense		
Total watts		
Average cost per kwh		
Total energy cost per year[a]		
Lamp renewal expense		
Net cost per lamp		
Labor cost each individual relamp		
Labor cost each group relamp		
Percent lamps that fail before group relamp		
Renewal cost per lamp socket per year[b]		
Total number of lamps		
Total lamp renewal expense per year		
Cleaning expense		
Number of washings per year		
Man-hours each (est.)		
Man-hours for washing		
Number of dustings per year		
Man-hours per dusting each		
Man-hours for dustings		
Total man-hours		
Expense per man-hour		
Total cleaning expense per year		
Repair expenses		
Repairs (based on experience, repairman's time, etc.)		
Estimated total repair expense per year		
Total operating and maintenance expense per year		
Recapitulation		
Total capital expense per year		
Total operating and maintenance expense per year		
Total lighting expense per year		

[a] $\text{Total energy cost per year} = \dfrac{\text{Total watts} \times \text{burning hours per year} \times \text{cost per kwh}}{1000}$

[b] The following formulas give the annual cost per socket for lamps and replacement, and can be used for determining the most economical replacement method.

$$\text{Individual replacement} = \frac{B}{R}(c + i) \text{ dollars/socket/year.}$$

$$\begin{array}{c}\text{Group replacement} \\ \text{(early burnouts replaced)}\end{array} = \frac{B}{A}(c + g + cKL + Ki) \text{ dollars/socket/year.}$$

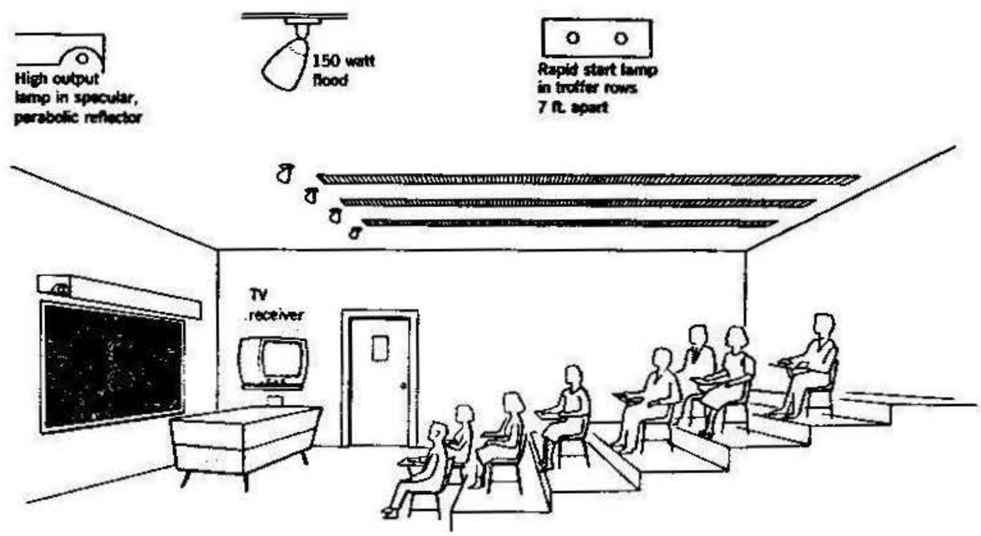
$$\begin{array}{c}\text{Group replacement} \\ \text{(no replacement of early burnouts)}\end{array} = \frac{B}{A}(c + g) \text{ dollars/socket/year.}$$

where B = burning hours per year
R = rated average lamp life, hours
A = burning time between replacements, hours
c = net cost of lamps, dollars
i = cost per lamp for replacing lamps individually, dollars
g = cost per lamp for replacing lamps in a group, dollars
K = proportion of lamps failing before group replacement (from mortality curve)
L = the portion of the cost of early burnouts that is charged against group replacement.

No general rule can be given for the use of group replacements; each installation should be considered separately. In general, group replacement should be given consideration when individual replacement cost i is greater than half the lamp cost c and when group replacement cost g is small compared to i.

Lecture Hall Lighting

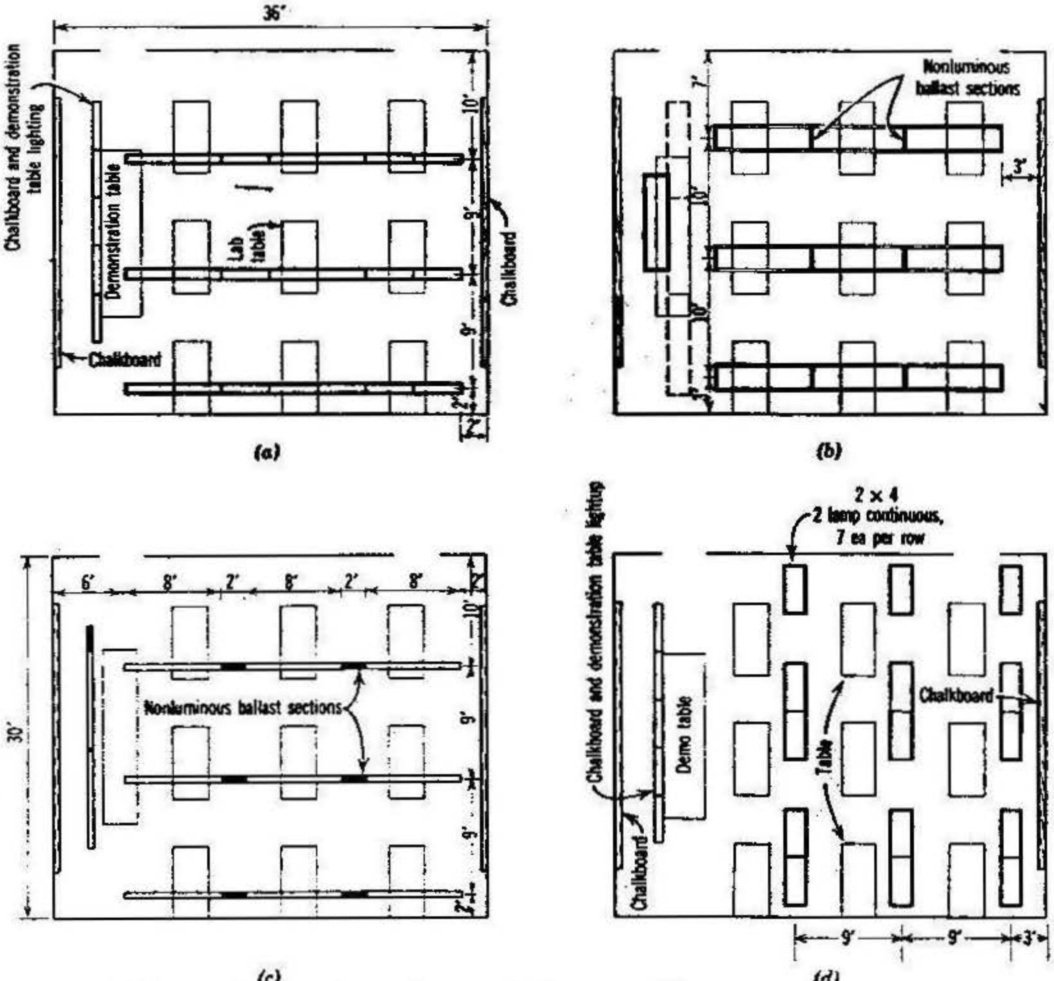
Lecture hall lighting is similar with respect to sources and other considerations to classrooms. Three-level fluorescent lighting which is readily accomplished via switching and multilevel ballasts, eliminates energy-wasting incandescents. Low levels are necessary during demonstrations, films, and the like. Auxillary lighting for demonstration table and chalkboard complete the design. Step lights are not normally utilized. High-ceiling installations can utilize mercury or metal-halide for general lighting. Controls for lighting should be at the demonstration table.



Lengthwise section through lecture room shows elevated seats toward rear, troffer general lighting in a suspended ceiling surface-mounted adjustable R-40 lamp units over demonstration table, and fluorescent chalkboard lighting.

Laboratory Lighting

Laboratories differ from classrooms in that tables are fixed, bench surfaces are frequently very dark, many of the items used exhibit specular reflection, vertical surface illumination is important, and visual task are not normally prolonged or severe. With low ceilings, use direct fixtures located parallel to and slightly behind the edge of tables to avoid reflected glare. These fixtures should have as wide a distribution as possible. If ceiling height is sufficient, indirect lighting will also provide a high degree of diffuseness necessary for vertical surface illumination. (See the figure below.)



Laboratory lighting schemes. Running lights across tables or in aisles is generally preferable from a reflected-glare aspect. Scheme (a) *utilizes pendant direct-indirect units, while* (b) *and* (c) *are variations of the single, semi-indirect HO and VHO unit design, illustrated in Table 20.7, Fixture No. 28. Relatively high noise level of ballasts is generally not objectionable in labs. Sketch* (d) *utilizes direct units in low ceiling, positioned for minimum glare.*

Library Lighting

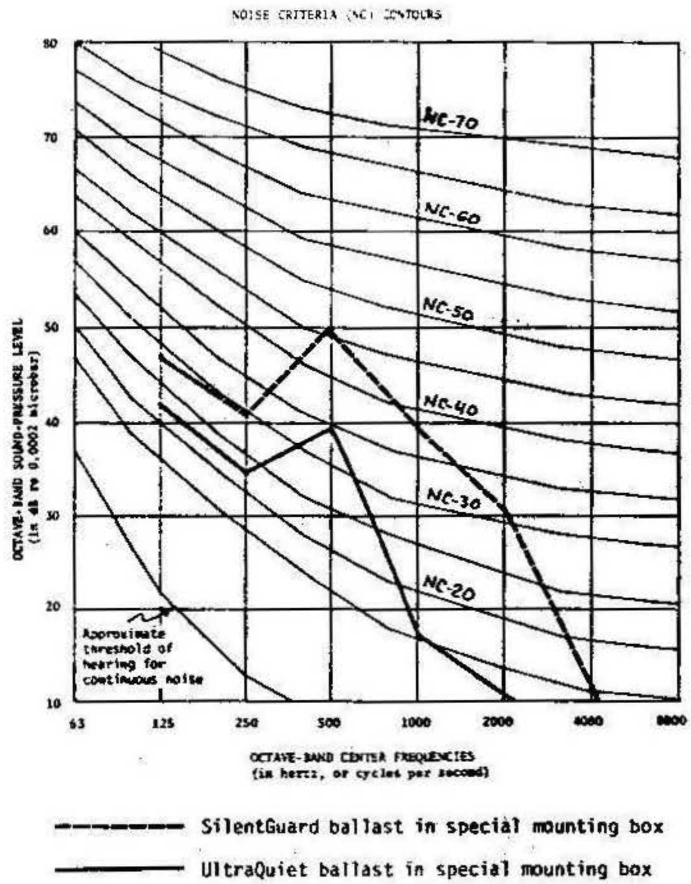
Libraries comprise several different seeing tasks, each of which requires its own lighting solution.

(a) General Reading Room

Here two solutions are possible and both are in common use. In the first, general lighting is supplied over the entire area, which is sufficient for reading tasks. For this purpose fluorescent or HID sources such as deluxe mercury or metal-halide (High-Intensity Discharge) are normally applicable, the latter two with ceiling heights at least 3.00M (10ft).

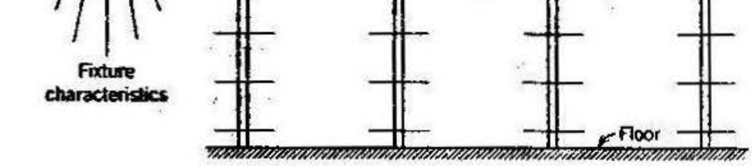
The long life and good color and efficacy of these sources are suited to the long burning hours found in libraries. The second solution involves low-level general lighting supplied by fluorescent of HID sources supplemented by local reading lighting on the tables or carrels. Reading lights should be fluorescent, arranged to avoid veiling reflections (see section on nonuniform office lighting in the next few pages).

Wherever HID sources are used, an additional instant restart source must be supplied to supply minimal lighting after an outage. The units shown in the figure above contain a small tungsten-halogen source for this purpose. Ballast noise can be a problem in low NC criteria spaces such as libraries. Special low-noise ballasts and eclosures are availabe and should be employed.



(b) **Stack Areas**

In stack areas required vertical surface illumination is best supplied by one of the special fluorescent units designed for this purpose. These are mounted between, and no higher than 24 inches (0.60 M) above stacks for best results. (see figure)



(c) **Card Index Files**
Vertical surface illumination is best supplied here by fluorescent or HID sources directly above and in front of the files.

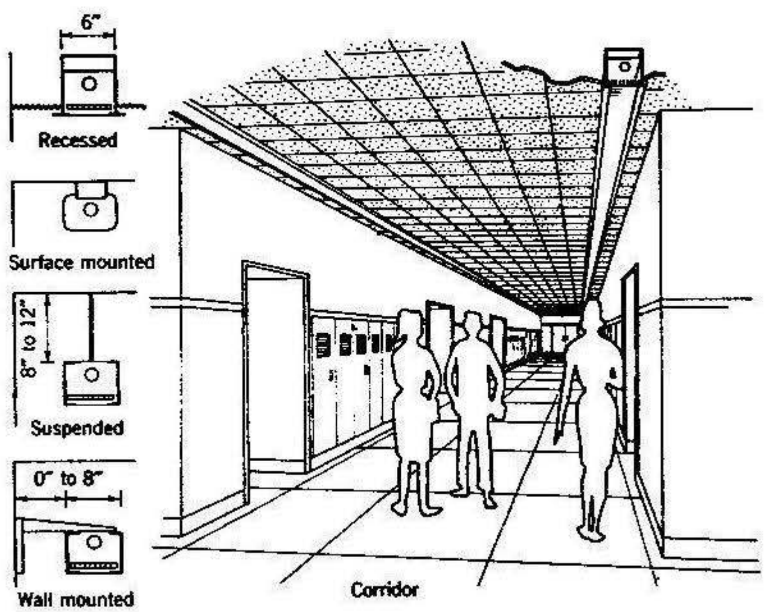
(d) **Work Desks and Checkout Areas**
The lighting requirements for this area are the same as those for the reading room except that levels are somewhat higher. Supplementary lighting is recommended.

Specialty Room Lighting

Rooms with specific tasks such as sewing and typing rooms and shops must be carefully considered. Where moving parts are present, adjustable local lighting may be necessary to aid seeing by reflection from specular work. No general rules can be suggested other than those previously explained in detail. Particular attention must be given to often forgotten vertical illumination requirements, which are vital in areas such as storage, stacks, and shops. Kitchens and cafeterias are color sensitive, and sources must be carefully chosen. If dining areas serve other functions they must be considered in the total lighting.

Corridors and Stairways — All Buildings

Corridors intended only for circulation need only be lighted to 10 fc ± unless a specific seeing task requires higher levels, for example, bulletin boards and lockers: (see figure)



Wall lighting with single lamp units

Stairs, as previously noted, require clear delineation of the treads, generally by shadowing. Lighting can also be used to give direction by longitudinal arrangement. Wall-mounted across corridors, particularly when corridors are long, are effective in reducing the tunnel impression. Incandescent sources are not recommended, because of low efficacy, high maintenance and frequency of relamping. Fluorescent and HID sources are also suggested for stairwells. Care must be excercised here, however, to avoid glare, which causes attention to shift from the stairs to the light and may thereby cause a hazard.

Commercial Interiors

Office Lighting

The following information applies primarily to offices in commercial buildings and secondarily to similar spaces in other occupancies, such as in educational and industrial buildings. In these latter cases, the general remarks applicable to those type facilities take precedence.

(a) **Sources:**
Use fluorescent in low-ceiling areas and HID or pendant fluorescent in high-ceiling spaces. Color is not critical. Warm-white and cool-white fluorescent and deluxe mercury or metal-halide are usable. HPS can be used to advantage when mixed with deluxe mercury or metal-halide to reduce possible objections to the yellow color. Because of high output, HID sources may create direct glare problems, which can be minimized by use of a low-brightness, lens-type diffuser (see figure).

Use low-wattage, energy-saving lamps as detailed in the section "U"-shaped lamps for fluorescents, Chaper 13. Incandescents may be used for storage areas, closets, and other short-burning is used to illuminate displays of all sorts.

(b) **Illumination Levels**

These are given in the Tables of required illumination levels, in the illustrative example of a classroom, Chapter 15, and recommended finishes for room surfaces are given in this figure.

Notice in the figure that the upper-wall dado has a lighter finish than the remainder of the wall. This serves the double function of increasing ceiling cavity brightness, particularly with suspended fixtures, and increasing vertical illumination due to reflection from this surface. The basic design approach should be for non-uniform lighting. See examples and explanations in Chapter 15, lighting design, for supplementary lighting design.

(c) **Vertical Surface Illumination**

This is required for visual tasks in offices, such as files, desk drawers, card files and secretarial copy stands. Large area luminaires and a high degree of diffuseness where wall reflections are absent. Light-finish furniture surfaces, surface-mounted fixtures, and high-reflectance floors will also assist in this.

(d) **Private Office**

Here the lighting should be carefully designed for the specific areas and work involved; general and supplementary lighting with variable levels for desks, downlights in sitting areas, wallwash for accent and brightening dark walls, special lighting for display boards, paintings, and so on. If the ceiling is high, pendant fixtures can create a horizontal plane to correct poor room proportions.

(e) **General Offices**

These areas can use ceilings and mounting heights for fixtures. Direct-indirect distribution pendant units provide good diffusion, low direct and reflected glare, and good vertical light component but are dirt catchers and are unattractive set near walls, additional peripheral lighting is frequently required.

(f) **Office Lighting Equipment**

This should not be handled roughly. Fixtures may have touch latches, light hinges, and adjustable devices without fear of breakage or vandalism

(g) **Maintenance**

In most offices maintenance is provided on a trouble call basis. Lamps are replaced on burnout, and the fixture is then cleaned. Because of the long life of fluorescents and HID sources, this generally means a 3-to-5-year cleaning cycle. Since most office use lay-in troffers, an LLF of 0.6 to 0.65 is reasonable in air conditioned spaces; lower in open-window offices.

(h) **Noise**

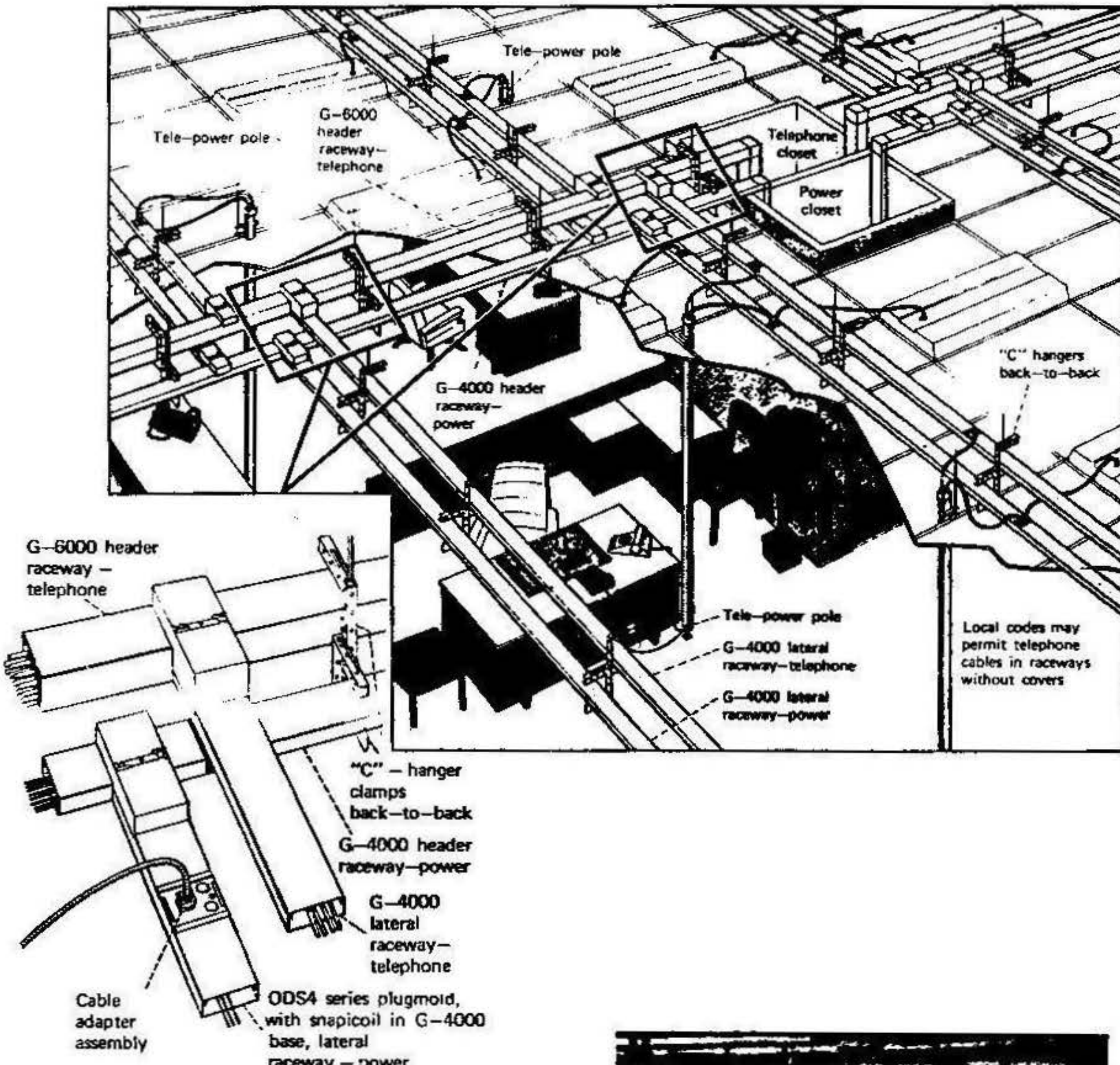
Noise from air conditioning plus adjacent street, traffic, and process noise, makes the use of higher-noise level ballasts, as are found on HO and VHO lamps, frequently feasible. For private offices, A-rated ballasts for 430-ma lamps are the best choice. (see chapter on building noise control)

(i) **Fenestration**

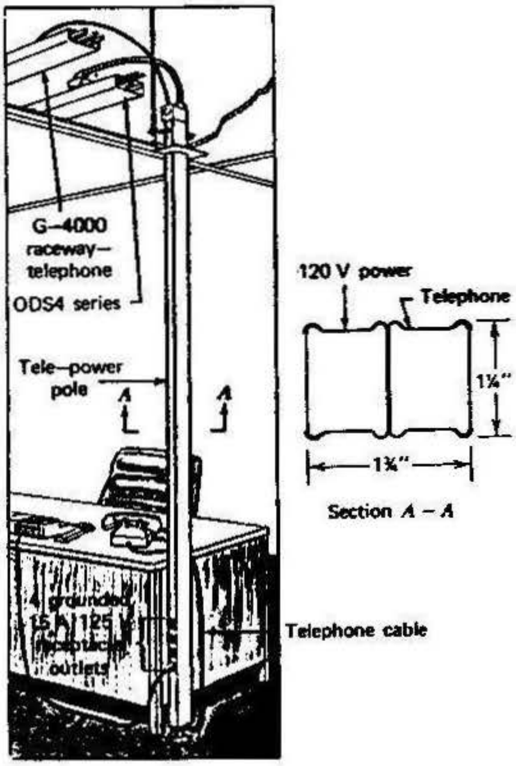
When fenestration is absent, a lighted valance is recommended around the room. This will remove the wall-ceiling line and will partially compensate for the lack of windows. It will also brighten the walls and increase illumination of desks placed adjacent to the walls.

(j) **Supplementary Lighting**

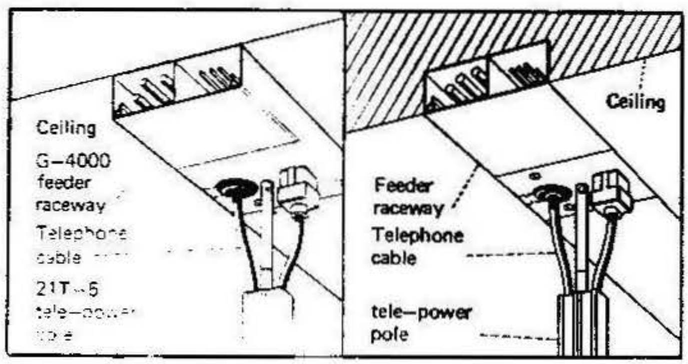
Supplementary lighting can be mounted on ceiling-track-fed poles of the type shown in the figures below. These are in effect, track lights, mounted on vertical tracks.



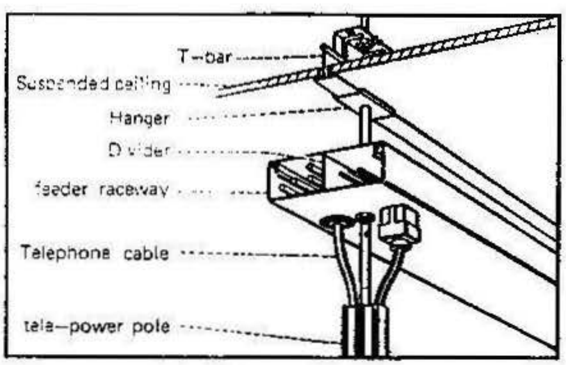
A single distribution duct with receptacle outlets, placed at 24-in. centers, feeds a large number of recessed troffers in this brightly lighted merchandising area ceiling. Hard wiring of this density of lighting fixtures would be considerably



Detail of one design (of many) of Wiremold's Tele-power pole. Other designs have different dimensions, outlets, bases, and colors. The power compartment is prewired with four single or two duplex 15a, 125 v outlets, with top connection as desired. In this case the power compartment is wired to a flexible armored cable terminating in a special polarized plug. The communications compartment is generally unwired. Pole lengths are available to match ceiling height requirement.



(b)



(c)

(k) **Switching**

Provide switching to allow for:

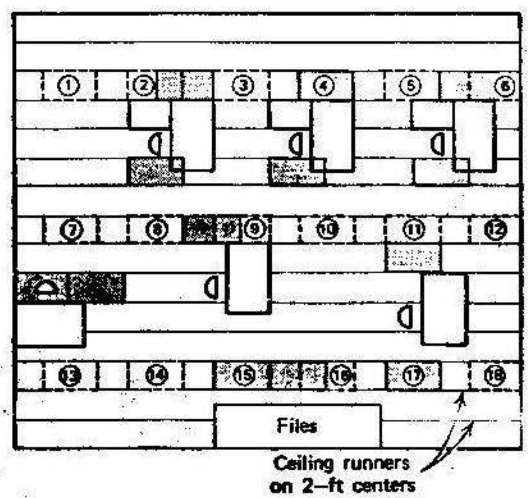
1. Small groups of lights to remain while the remainder are off.
2. Path lighting through large spaces to permit traverse without turning on all lights.
3. At least two levels via alternate lamp switching in areas where tasks severity changes or where daylight contibution varies. This is definitely preferable to entire fixture switching.
4. Central control to permit switching of large blocks of lighting.

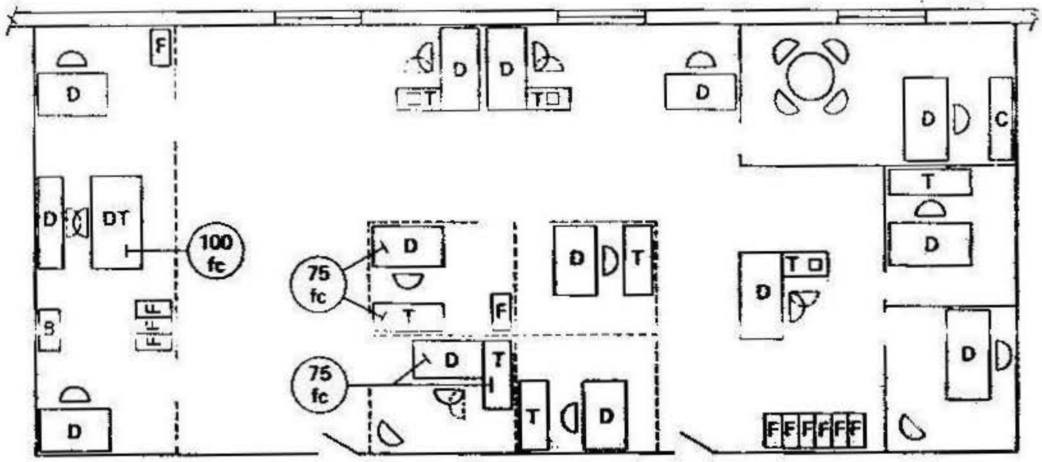
Nonuniform Office Lighting Design Using Ceiling-Mounted Units

Modern office lighting design is predicated on nonuniform layout. This approach has three advantages:

a. Higher ESI
b. Lower first cost
c. Lower power and energy, yielding lower operating costs.

The general or ambient lighting can be either be a uniform layout at a low level, the spill light from local lighting, or a combination of both. See figures below. The first figure (a) is an example of the former; the other figures (b), (c) and (d) of the latter.

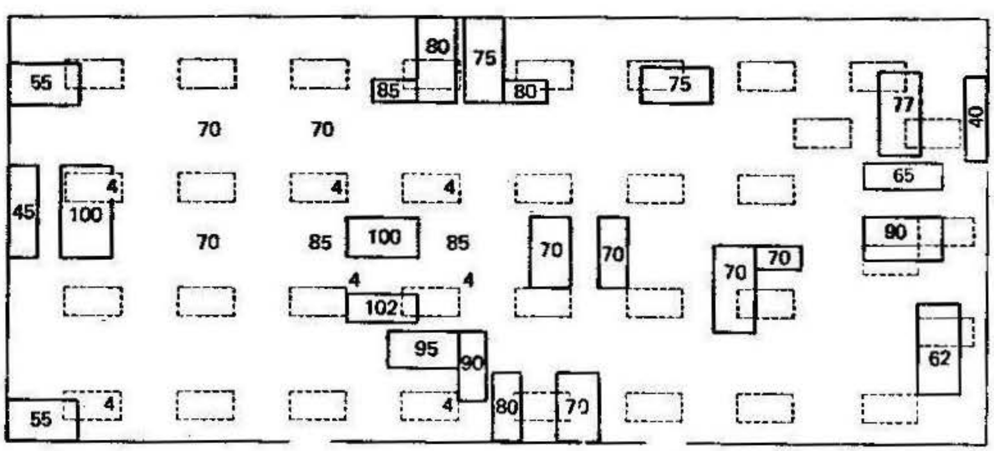




C Credenza
T Ref. table
D Desk
D T Typing station
F File cabinets
B Book case
DT Drafting table
Ceiling height partitions
5' 0" High partitions
Overall room dimensions 30' x 70 x 9' high

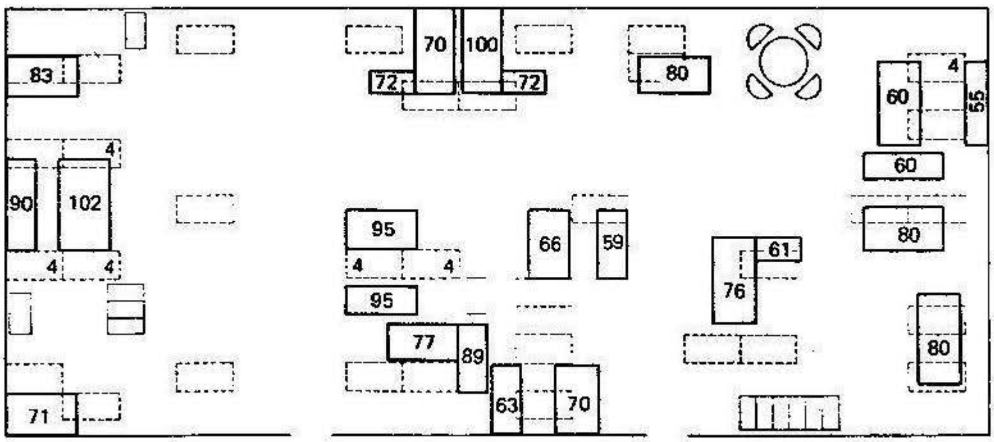
NOTE: Illumination levels on all task surfaces shall be 50 fc except as noted.

Refer to figure (b), which is an office layout for a small technical office. In accordance with current recommendations, 50 fc is to be furnished on all work surfaces except the drafting table DT, and two small offices where close work on poor copy will be performed. Figure (c) shows a standard uniform layout; generally using three-lamp, 2 x 4 feet (0.60 x 1.20 m). Fluorescent troffers, with high-quality lens diffusers. VCP is good due to low lens brightness. Illumination on the drafting table is also good because of the fortuitous position of the fixture above it. Other work surfaces receive more than adequate raw footcandles but in many instances low ESI due to bad ceiling reflections.

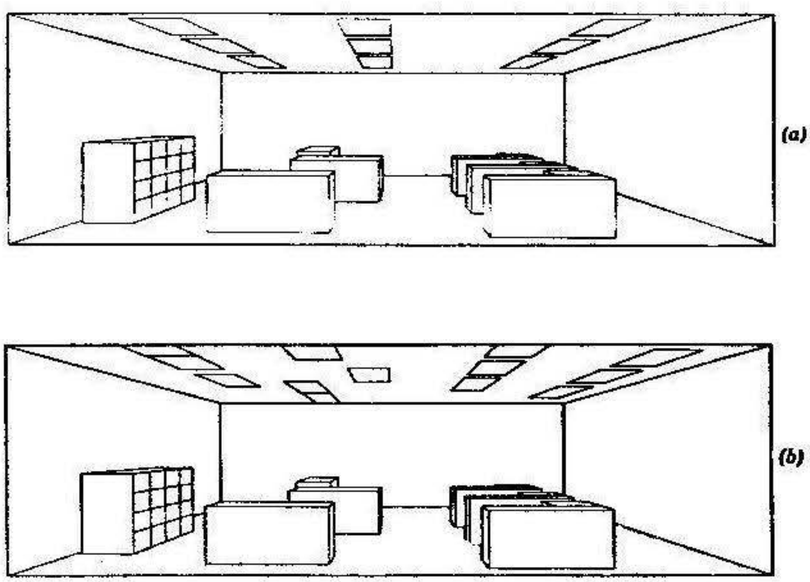


All 3–lamp F40 cw fixtures except where marked "4".
Footcandles are average over the desk.
35 fixtures; 5600 w total; 2.66 w/sq ft.
VCP > 80.
ESI – position dependent; generally poor to fair.
Average task illumination – all task; 75 fc raw, approx 45 in. ESI.

In figure (d), fixtures have been arranged to supply task lighting. Ambient lighting comes from spill light and three fixtures placed in a relatively large, open circulation space. The results are good VCP, much higher ESI footcandles on the tasks, and somewhat lower energy use.

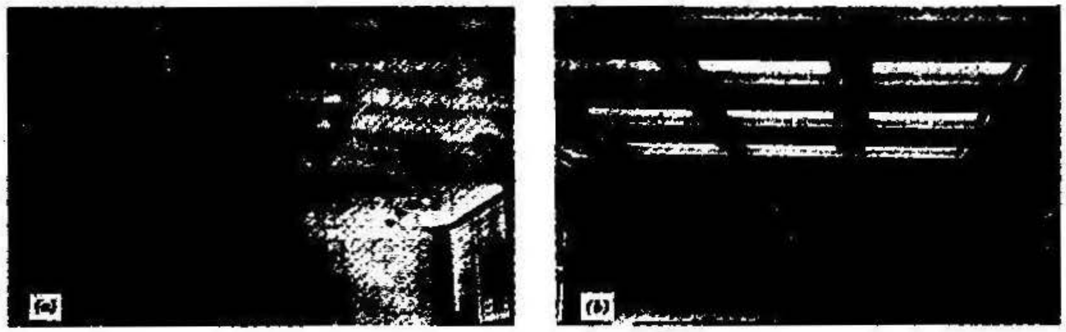


As pointed but in the figure below, a disadvantage of this system is the jumbled appearance of the ceiling.



(a) The uniform layout of Figure— is neutral in that it does not dominate the space or draw the eye.
(b) The nonuniform layout can be dominant in the pejorative sense if the eye is drawn by the lack of pattern or symmetry.

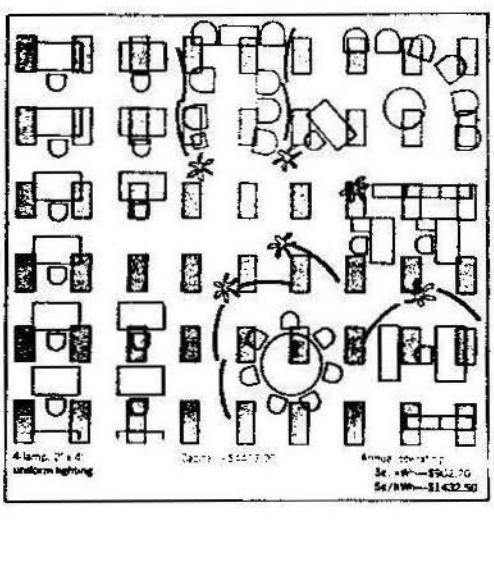
For this reason, nonuniform layouts are well suited to coffer-type ceilings, as in the figures below, where the presence or absence of a fixture is not as prominent. This is all the more important where large glass wall areas make the ceilings readily visible from the outside. (See also the various configurations of 5 ft. square modules in the following pages).



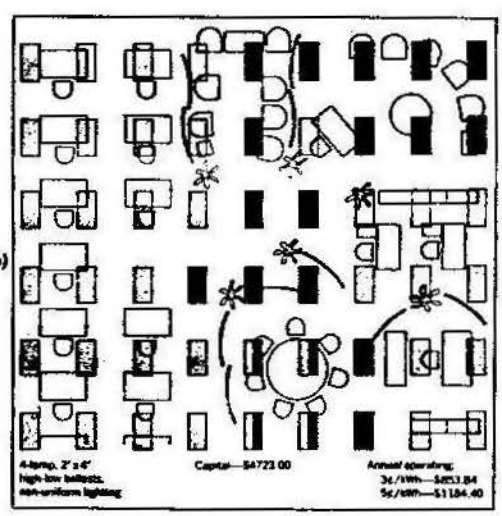
A coffer ceiling room (a) is illuminated with 1 x 4, 2-lamp units in alternate coffers. the appearance unlighted (a) and lighted (b) is symmetrical and pleasing. A nonuniform layout would be less objectionable here than in a flat hung ceiling.

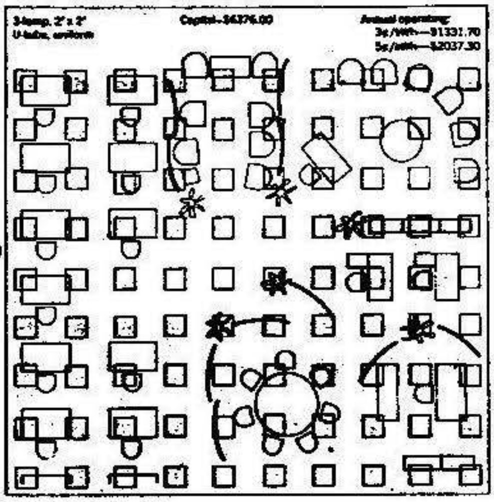
This appearance problem can be mitigated considerably by using a uniform arrangement with adequate switching to provide the levels desired. This type of system illustrated below, as added advantage of usefulness when the furniture layout is not known in advance a common occurence. Its disadvantage is higher cost for fixtures, multi-level ballasts and switching, and lack of fixture-position control, so important in achieving low reflected glare.

(a)

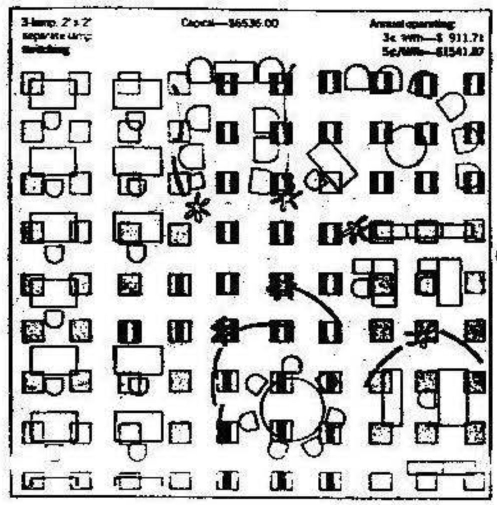


(b)



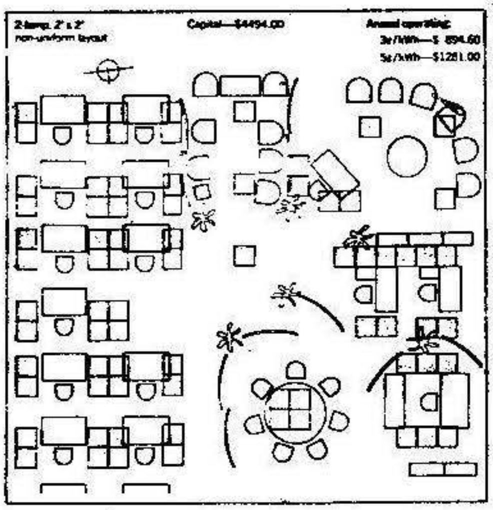


(c)



(d)

The figure below, is another technique in minimizing the appearance problem of nonumiform layout. Smaller sources are less objectionable when symmetry is absent.



Nonuniform Office Lighting Using Furniture-Integrated Luminaires

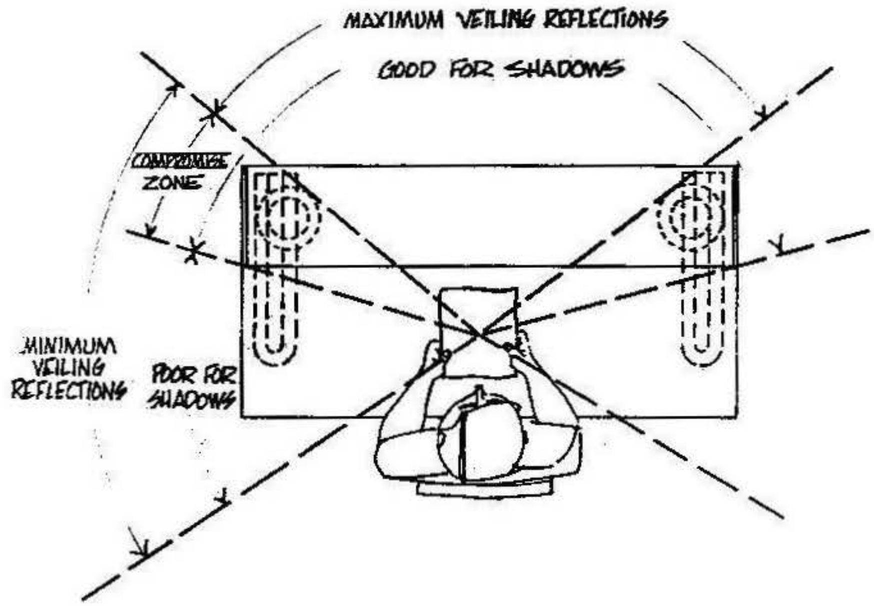
In lieu of ceiling-mounted fixtures, ambient and task lighting can be supplied by furniture-mounted units. This system has these ADVANTAGES:

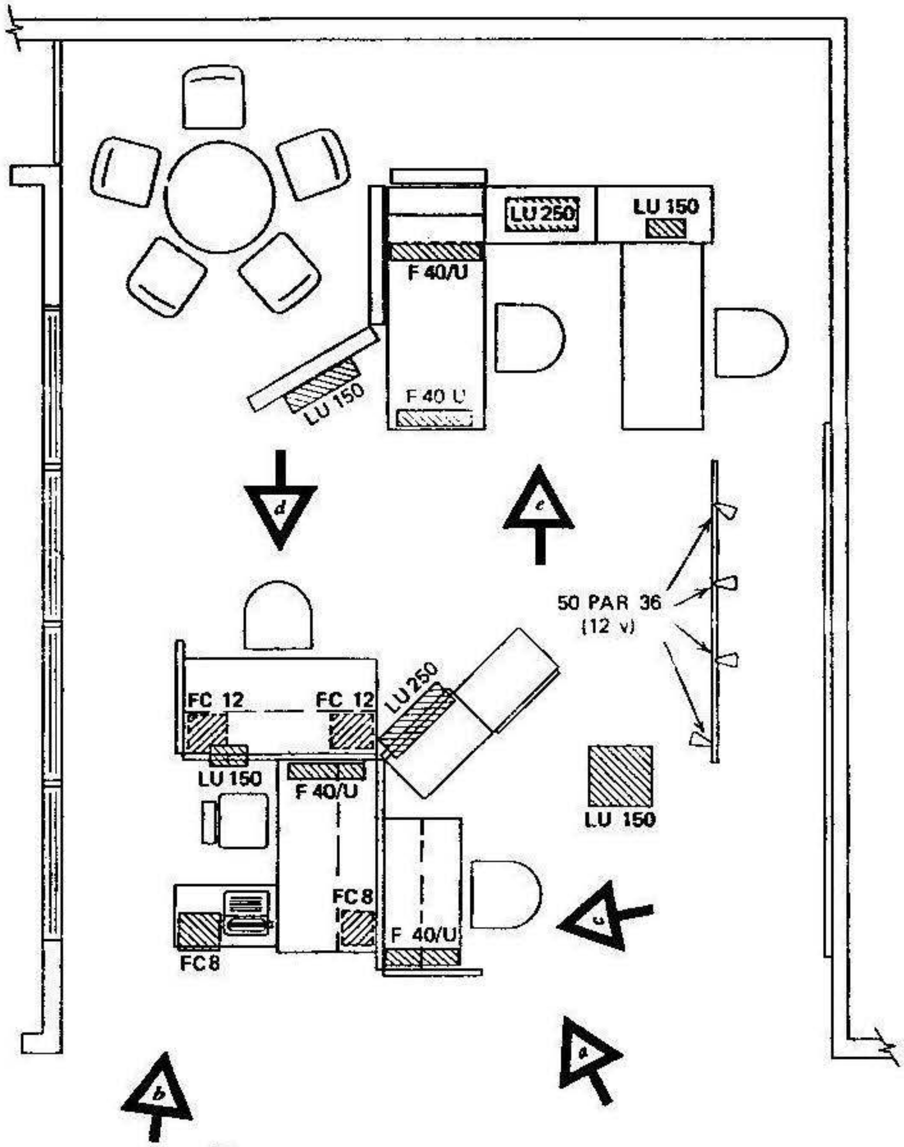
a. The problem of furniture layout and layout changes is eliminated.
b. Initial construction cost is reduced
c. Energy requirements are lowered because of short distances between light source and task.

d. Each occupant has ON-OFF control of his or her task lighting and, in some designs, positioning control as well.
e. Maintenance is very much simplified, since fixtures are readily accessible from the floor.
f. Floor-to-floor height can be frequently be reduced
g. Tax advantages normally accrue due to higher depreciation rates on furniture than on the building.

DISADVANTAGES include:

a. Difficulty in dissipating heat and minimizing ballast noise due to proximity of sources to user.
b. Veiling reflections can be severe.
c. Brightness ratios in the near and far surround may exceed recommended levels.
d. Difficulty in lighting a free-standing open desk, since most of the fixture types are undercounter or side-wall mounted. See figure (e) from the paln of a prototype space in the next pages.
e. Difficulty in evenly lighting large table or L-shaped desk areas because of the concentrating nature of the lighting units.

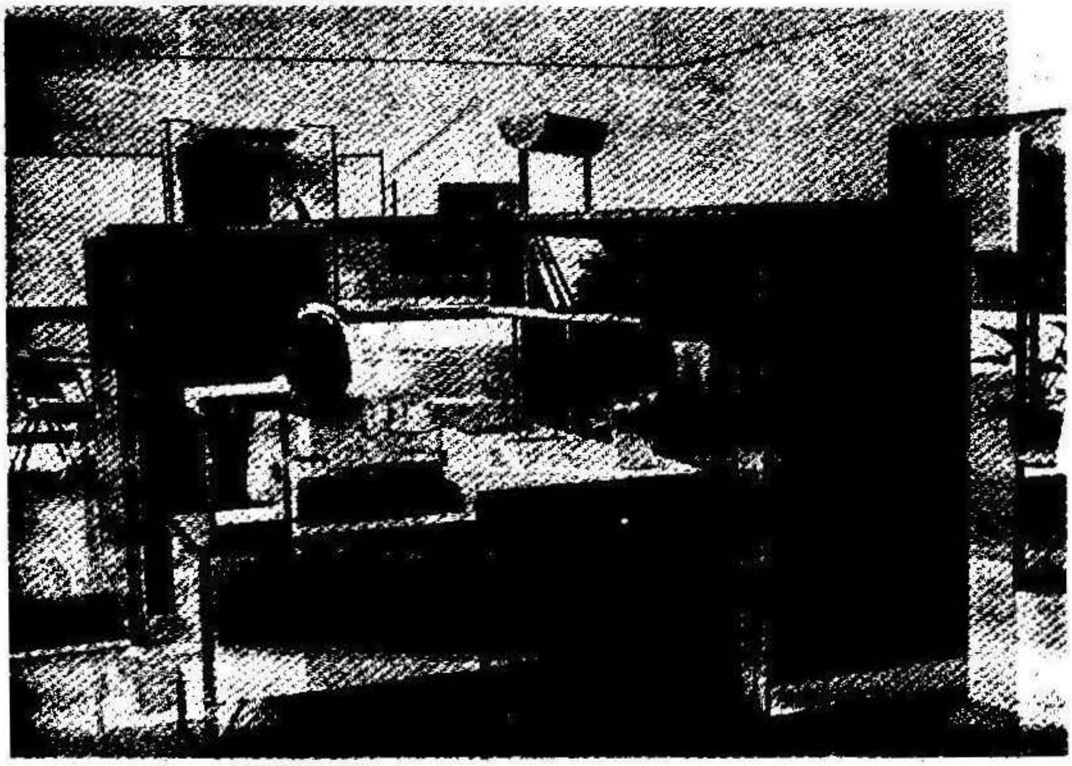




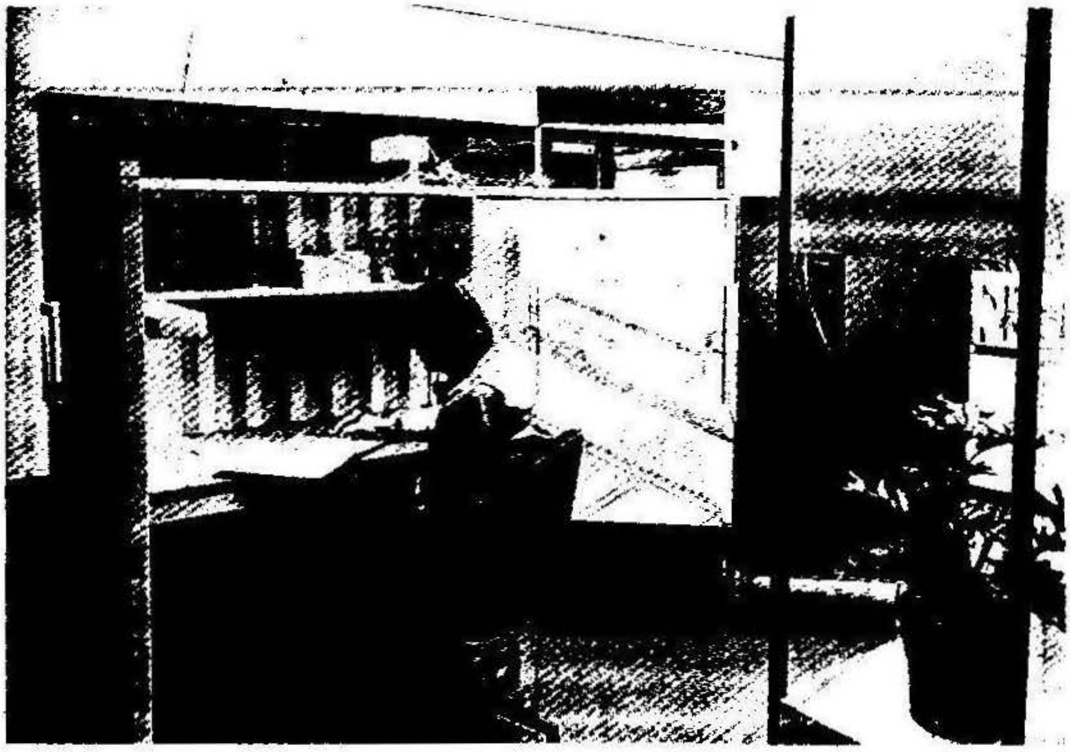
Lamp Data:

LU 250 – High–pressure sodium, 250 w, ~ 25,000 lm
LU 150 – High–pressure sodium, 150 w, ~ 14,000 lm
F 40/U – U–shaped fluorescent, 40 w, ~ 3200 lm
FC 12 – Circular fluorescent, 12 in. diam, 32 w, ~ 1800 lm
FC 8 – Circular fluorescent, 8 in. diam, 22 w, ~ 1000 lm

The figure below is a plan of a prototype office space using this system, with views of this office mock-up, taken at the points indicated. The reader may judge the effectiveness of this particular design, which is one of many now appearing commercially.



Task lighting arrangement for the secretarial work station is a U-lamp fluorescent luminaire and a circular fluorescent lamp luminate to light tasks at the desk with minimal-size equipment and minimum ceiling reflections. Another open bottom unit utilizing the 8-in circular fluorescent lamp is in a laterally tracking unit to locate to the right or left of the typewriter for copy illumination.



Task lighting for the sales work station from the U-lamp unit at the left provides light with minimal veiling reflections. It is reinforced by the under-shelf two-lamp, 20-w, side mount unit located above the lateral file storage unit in the center of photo. There can be opportunities such as this for lighting such tasks that do not lie on the work station work surface; but where there is not, a sufficient amount of ambient illumination is then needed.

Integrated and Modular Ceilings

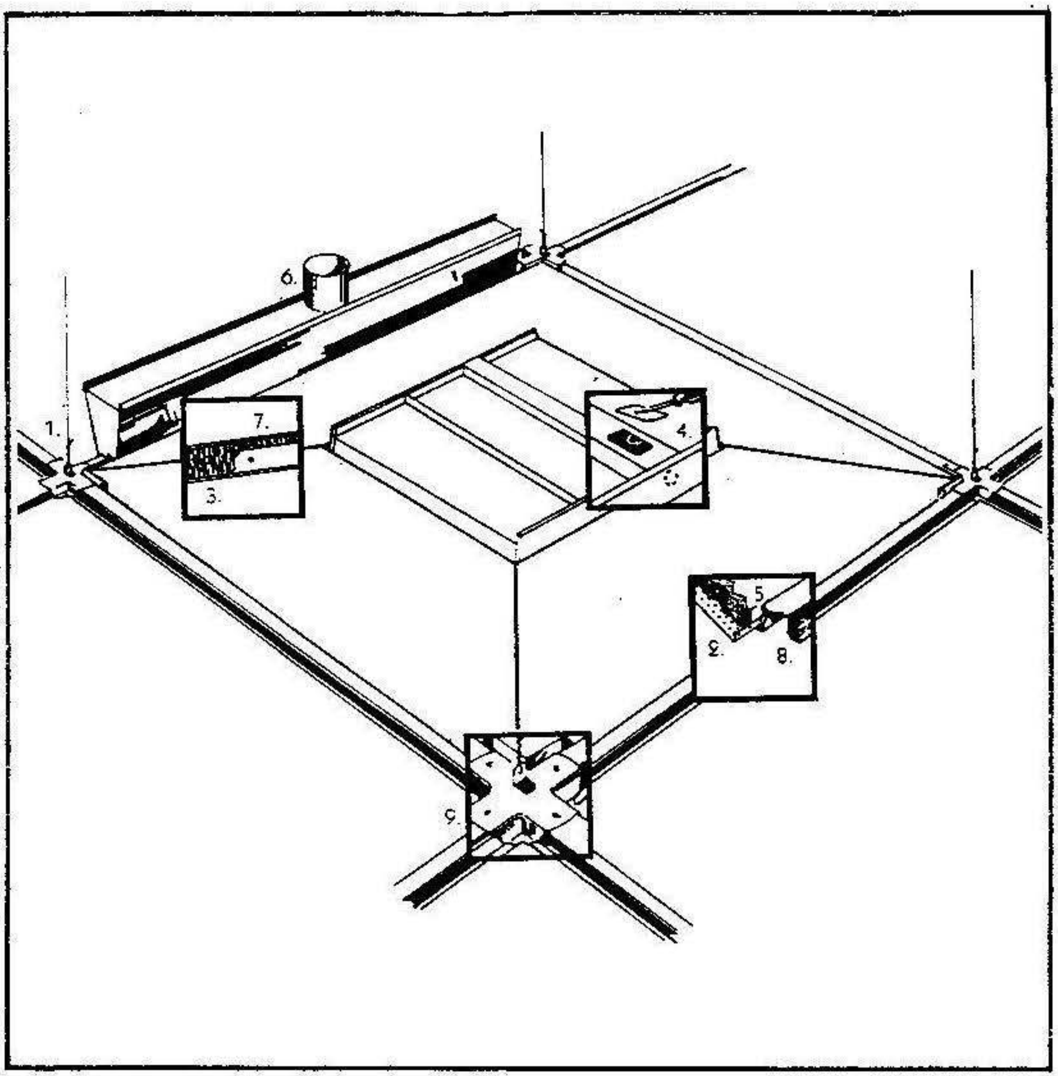
The cost, appearance, and design-flexibility advantages of an integrated ceiling design over field-assembled and coordinated systems has long been known. As a result ceiling systems with integrated lighting, acoustic control, and air-handling capabilities have been made commercially available in modular sizes, among which are 60 inch square (1.50 x 1.50 m), 48 inch square (1.20 x 1.20 m) and 30 x 60 inch modules (0.75 x 1.50 m) are made in flat and pyramidal shapes, the latter having several distinct advantages over the flat:

a. More interesting and aesthetically pleasing.

b. More acoustic absorbency due to ceiling angles and large surface area.

c. Recessed center provides visual baffling, permitting use of higher brightness sources while maintaining high VCP.

A typically equipped pyramidal module is shown in the figure next page.

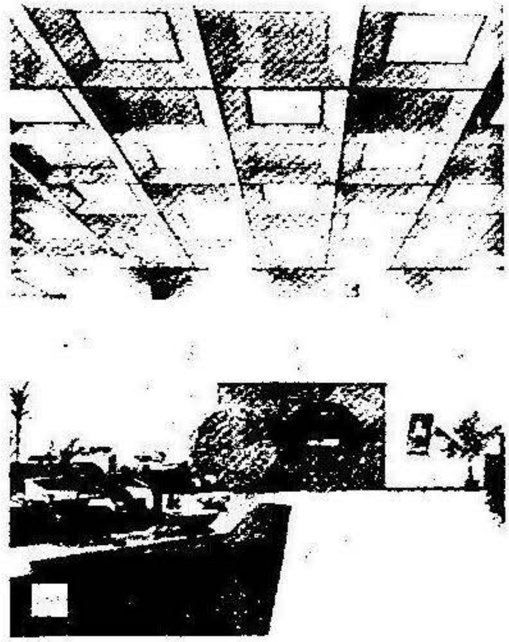


Plenum view of typical pyramidal module. Courtesy of Goth Lighting.

1. *Typical hanger wire connection.*
2. *Perforated metal acoustical coffer.*
3. *Fiberglass sound-absorbing insulation material.*
4. *Wiring access plate for fast electrical connection of lighting fixtures.*
5. *Sound-attenuating panel prevents noise travel from the room to room through plenum.*
6. *Air diffuser available in insulated or noninsulated versions.*
7. *Preassembled splay is ribbed for strength and rigidity.*
8. *Truss channel sides painted black to give splay a floating appearance from floor level.*
9. *Truss channel screws or rivets to intersection for fast accurate assembly of grid.*

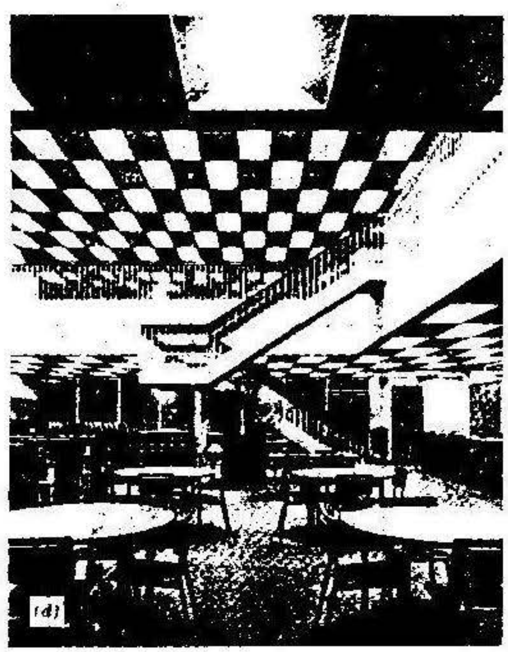
Possible luminaire arrangement for both flat and pyramidal shapes are given in this figure, with examples of installations.

(a) *2 ft square fixture with 'U'-tubes. Note low brightness of the miniature parabolic egg-crate diffuser.*

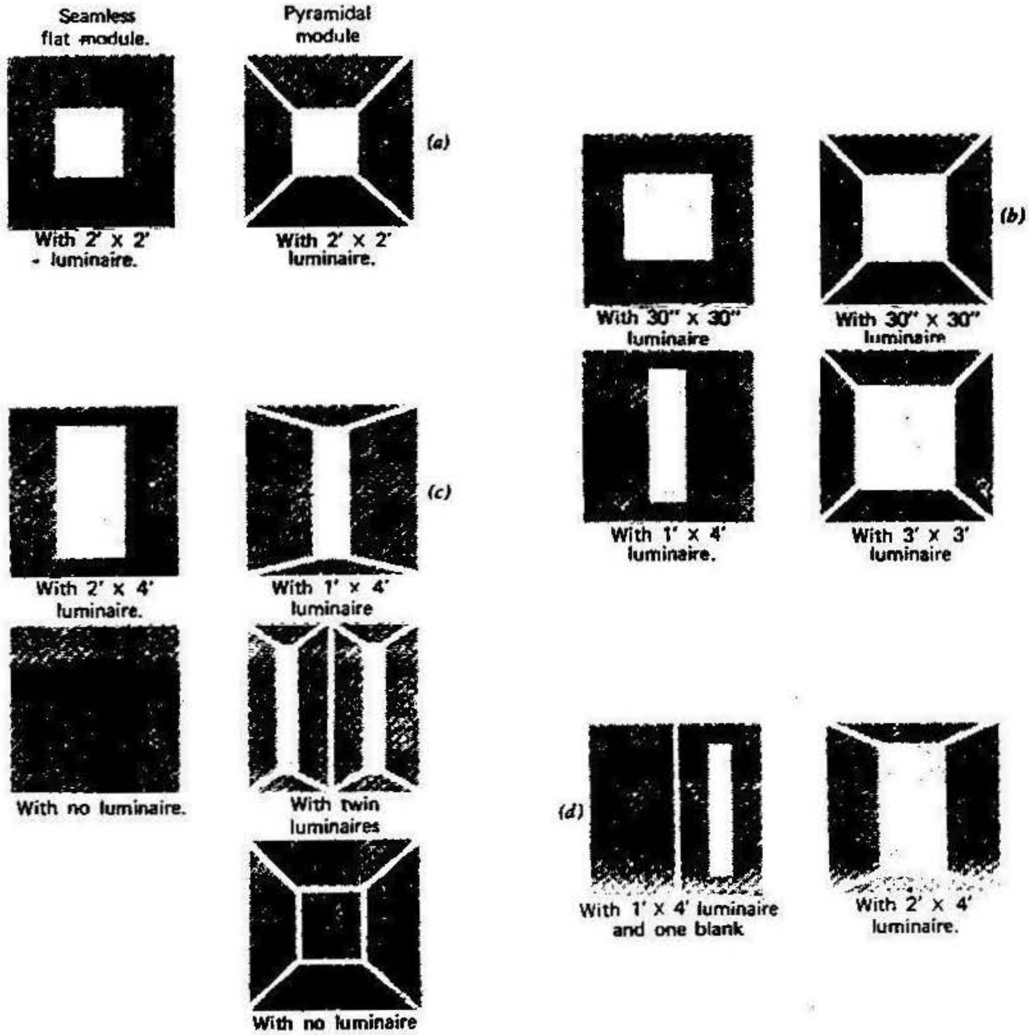


(b) *30-in. square luminaires alternating with blank section. Note the air intake along the module perimeter.*

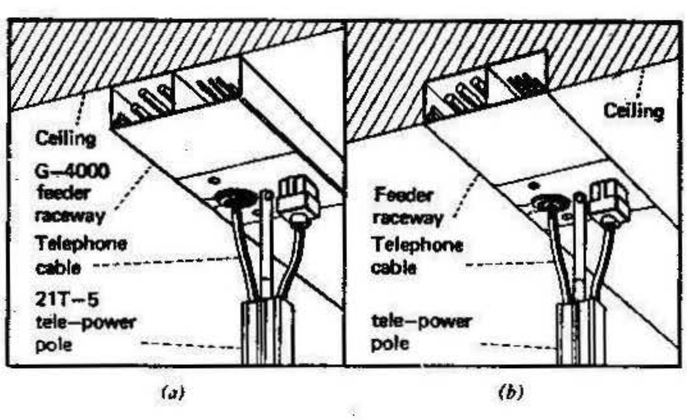
(c) *Note the shielding provided by the recess in the pyramidal shape. The effect is most pronounced with a low ceiling. Compare to* (b) *above.*

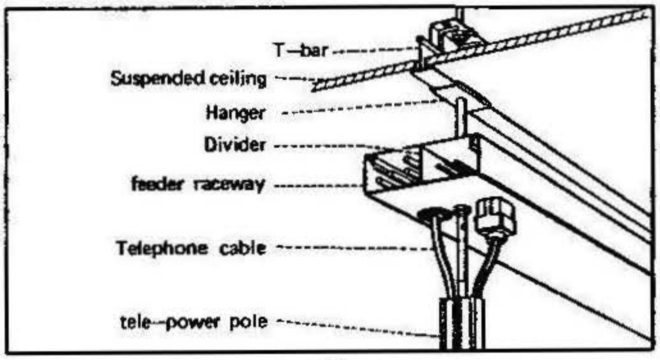


(d) *Splitting the module in half, rather than centering the fixture as in* (c), creates the dominant checkerboard pattern shown. Photos (a) to (d).



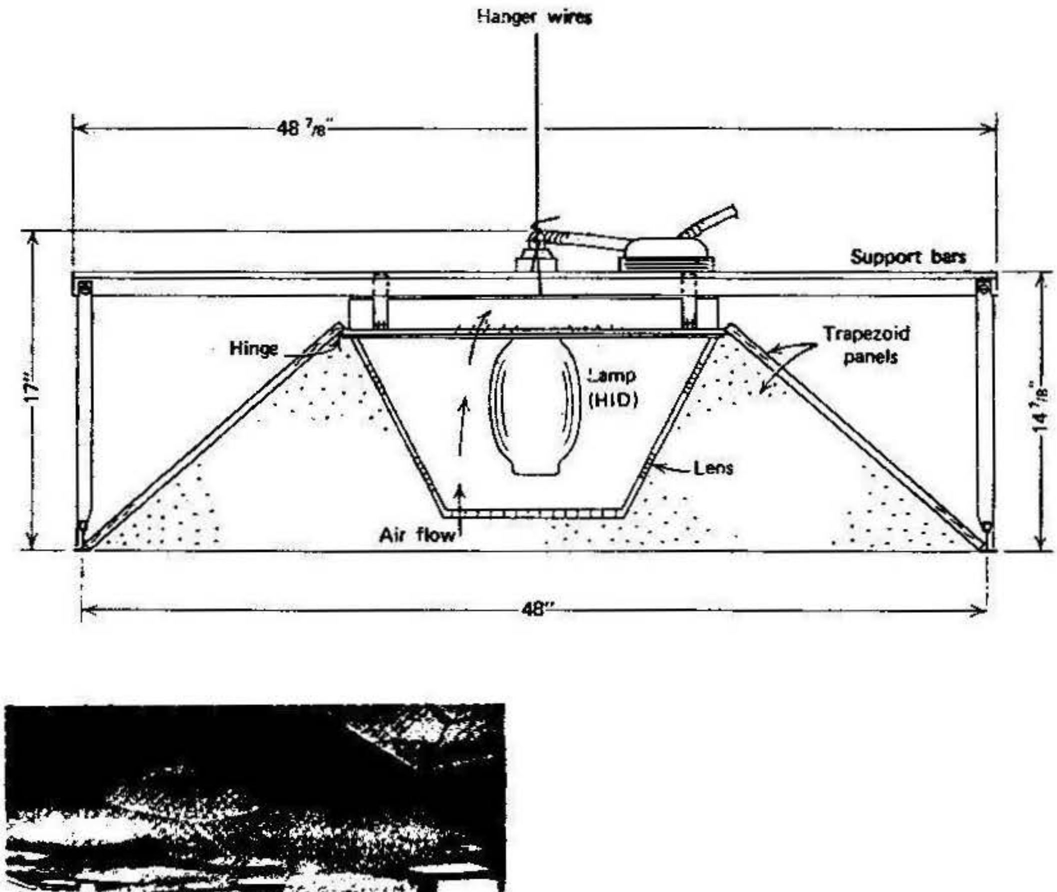
In addition to the design flexibility available, electrified track can be integrated into the system rumers, to supply both the lighting fixtures and power poles, as in the figure below. This is increases the mobility of the fixtures, so necessary for adequate task lighting.





(c)

The partial recessing accomplished with pyramidal modules is particularly useful when applying high-brightness HID sources to commercial interiors see the two figures below.



Lighting and Air Conditioning

The reduction of lighting density levels to below 3 w/sq. ft. in all but special areas has considerably reduced the impact of lighting generated heat on a building's HVAC system. In non air-conditioned buildings, the lighting heat contribution is directly applicable to building heating. Fixture efficiency is directly affected by its temperature. Fluorescent units operate at an optimum temperature of 77°F. Temperature above and below this decrease output and fixture efficiency. Thus heat removal from units is desirable even at low lighting-energy levels. The most effective method of fixture heat removal is by duct connection to the unit itself. This method, however, is relatively expensive, and immobilizes the fixture. Alternatively the plenum can be exhausted with air passing through the fixtures, picking up excess heat. These details are essentially part of the HVAC design.

INDUSTRIAL LIGHTING

General

In industrial lighting the prime and over-riding consideration of all work, lighting included, is its profitability; that is, its economic impact on the company. Given acceptable standards of comfort and safety for the working staff, additional costs for lighting must be self-justifying economically. In one case a good lighting installation was improved at considerable cost. Production jumped 15%, of which 3% was sufficient to amortize the cost of the lighting alteration. In another case an outlay for new inspection lighting reduced product failures and proved economically sound. In a third, improved lighting reduced accidents, improved employee morale, and consequently improved production. The cases studied are far too numerous to mention; general principles will be adduced instead.

Industrial Lighting Levels and Sources

With increased lighting levels, and control of glare problems, industrial workers are approaching the lighting condition under which their forebears worked-out-of-doors. That enviable situation, with 100 ± fc horizontally and vertically and low glare, is not attainable with artificial lighting at its present technology without grossly excessive cost and enery use — nor is it necessary. A lesson to be learned, however, is the need to utilize daylight to a much greater extent than is now generally the case.

Industrial facilities lend themselves readily to daylighting, since many are one-story structures. Thus roof monitors, skylights, and clerestories are readily applicable and extremely desirable. However, since industrial facilities are frequently sited in industrial areas with attendant heavy atmospheric soot and dirt, a frequent cleaning and maintainance program is necessary if the LLF is to be kept at reasonable levels. This observation is obviously also applicable to indoor light facilities (to the extent that the door activity warrants).

Sources for industrial application should be high-efficacy, low-maintainance types, that is HID and fluorescent. Where color is not critical, HPS is the recommended source. Adaptation to its warm yellow color is rapid, and, as stated above, if it is mixed with metal-halides or mercury sources are easier to maintain, store, clean, and relamp than fluorescent and have equal or better efficacy, but have the disadvantage of delayed restike time. Because of their concentrating nature, HID sources are more applicable to high-bay (>25 ft) and medium-bay (15-25 ft) installation, while fluorescent are suited for low-bay (<15 ft), although specially designed low-bay HID fixtures are available, hich minimize the inherent glare and distribution problems involved.

Industrial Illumination

Brightness Ratios

Brightness ratios in industrial situations must be cotrolled. Recommendations are given in the table below, In many situations it is impossible to control the surrounding brightness, as is shown in the tables. Note from table that ceilings that so frequently are covered with piping, ducts and other equipment must be light. In other words, the above equipment must be painted with high-reflectance finishes, maintainance and cleaning must be good, and fixtures should have an upward component of light to avoid more than a 20:1 ratio of task to ceiling luminance.

Industrial Lighting

Recommended Maximum Luminance Ratios

	Environmental Classification		
	A	*B*	*C*
1. Between tasks and *adjacent darker* surroundings	3 to 1	3 to 1	5 to 1
2. Between tasks and *adjacent lighter* surroundings	1 to 3	1 to 3	1 to 5
3. Between tasks and more *remote darker* surfaces	10 to 1	20 to 1	*
4. Between tasks and more *remote lighter* surfaces	1 to 10	1 to 20	*
5. Between luminaires (or windows, skylights, etc.) and *surfaces adjacent* to them	20 to 1	*	*
6. Anywhere within normal field of view	40 to 1	*	*

Industrial Lighting

Recommended Minimum Reflectances of Surfaces, Applicable to Classifications A and B of Table 21.4a

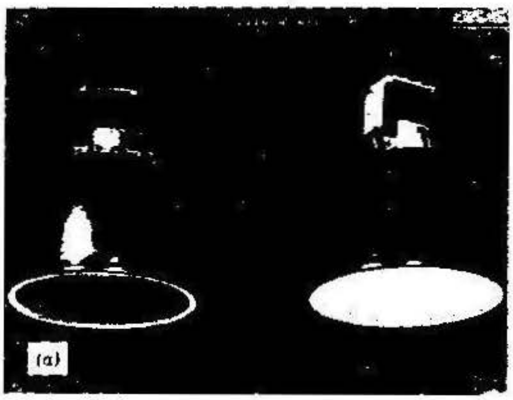
	Reflectance
Ceiling (all area above fixture line)	80 to 90%
Walls	40 to 60%
Desk and bench tops, machines and equipment	25 to 45%
Floors	Not less than 20%

Use of bright saturated colors for general surface painting should be avoided, however, since they draw attention and frequently have special significance. In addition to color-coded piping (banding is preferable), red frequently means fire equipment; green, first aid; orange, danger; etc. White is also to be avoided, being excessively bright and susceptible to dirt. Light, unsaturated colors are preferable.

Industrial Lighting

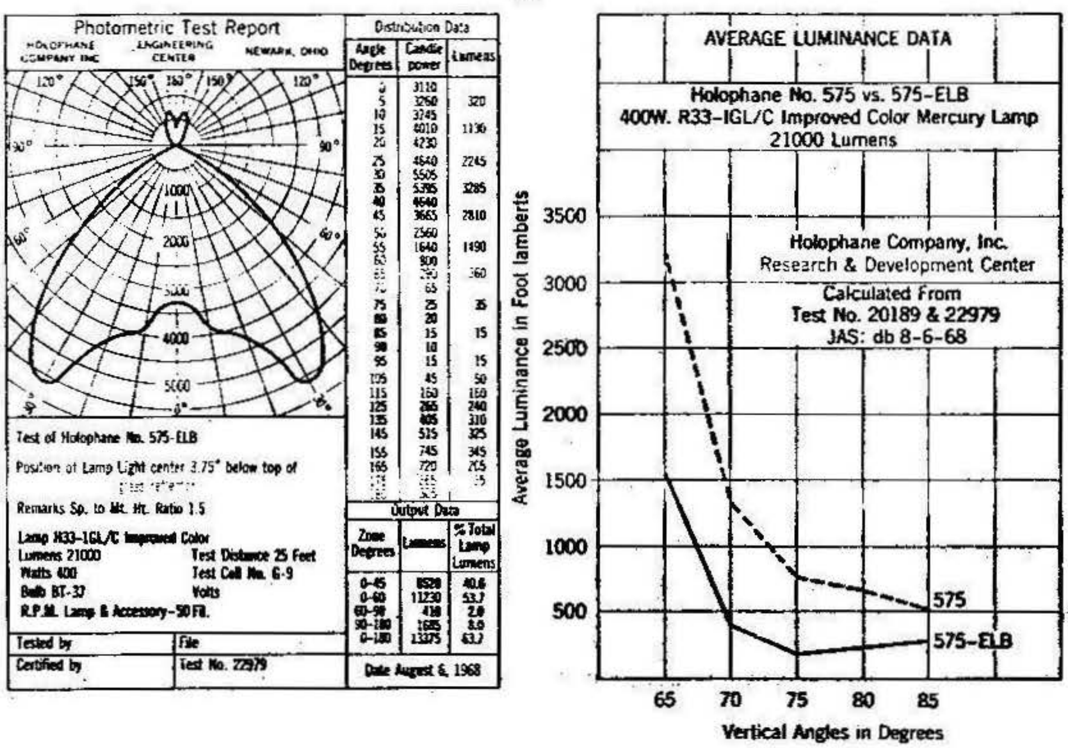
Glare

The problem of direct glare can be acute in low-bay installations, and that of reflected glare in high-bay designs, when both use point sources. One method of reducing direct glare is the use of low-brightness prismatic lens units that utilize a black aluminum reflector behind the prismatic lens. The pronounced reduction in high angle brightness of such luminaires (shown with 400-w mercury lamp) is shown in the figure below. This reduction in brightness is accomplished with only a 10% reduction in useful light.



(a) By utilizing a black reflector surface behind the prismatic glass lining in lieu of a polished aluminum one, fixture brightness can be dramatically reduced without great light loss. (b) Photometric comparison of the two lamps shown in (a).

(b)

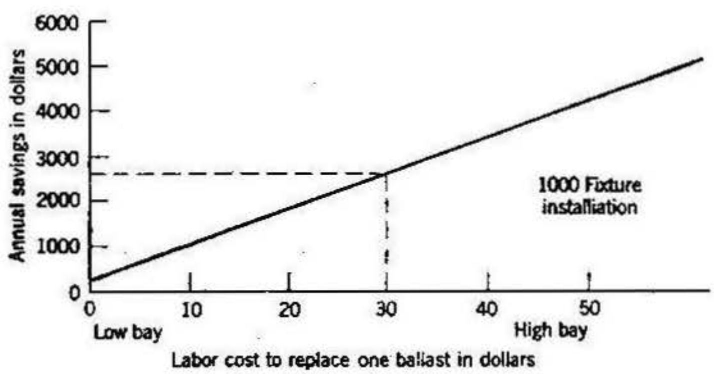


Another low-brightness unit with its photometric characteristics and an application using an HPS source are shown in the figure below. Methods of minimizing veiling reflection from all sources have been discussed previously.

Industrial

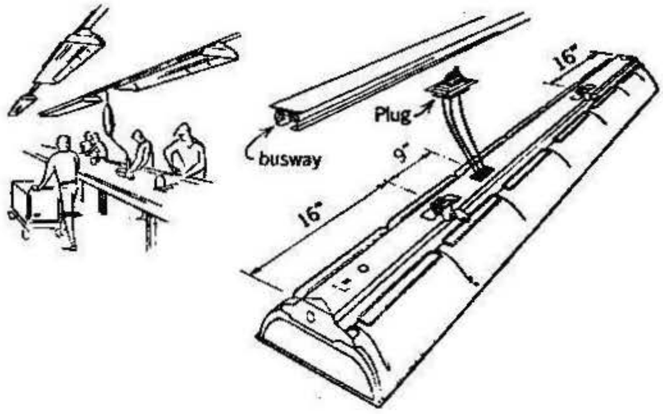
Lighting Equipment

The cost of maintainance increase with labor rates. For this reason, high-quality lighting equipment will yield lowest owning and life-cycle costs. For instance, the cost of replacing a ballast for an HID lighting unit frequently exceeds the cost f the ballast. It is thus obvious that it is more economical to utilize long-life, high-quality ballasts, particularly where luminaires are mounted high or are otherwise not readily accessible. This is graphically demonstrated in the figure below, which relates annual savings for a 1000-fixture installation to the labor cost for ballast replacement, when using higher priced, long-life ballasts. Thus for a medium-bay installation, at a replacement labor cost of \$30 (P600.00), not including production loss, an annual saving of \$2600 (P52,000.00) is realized.

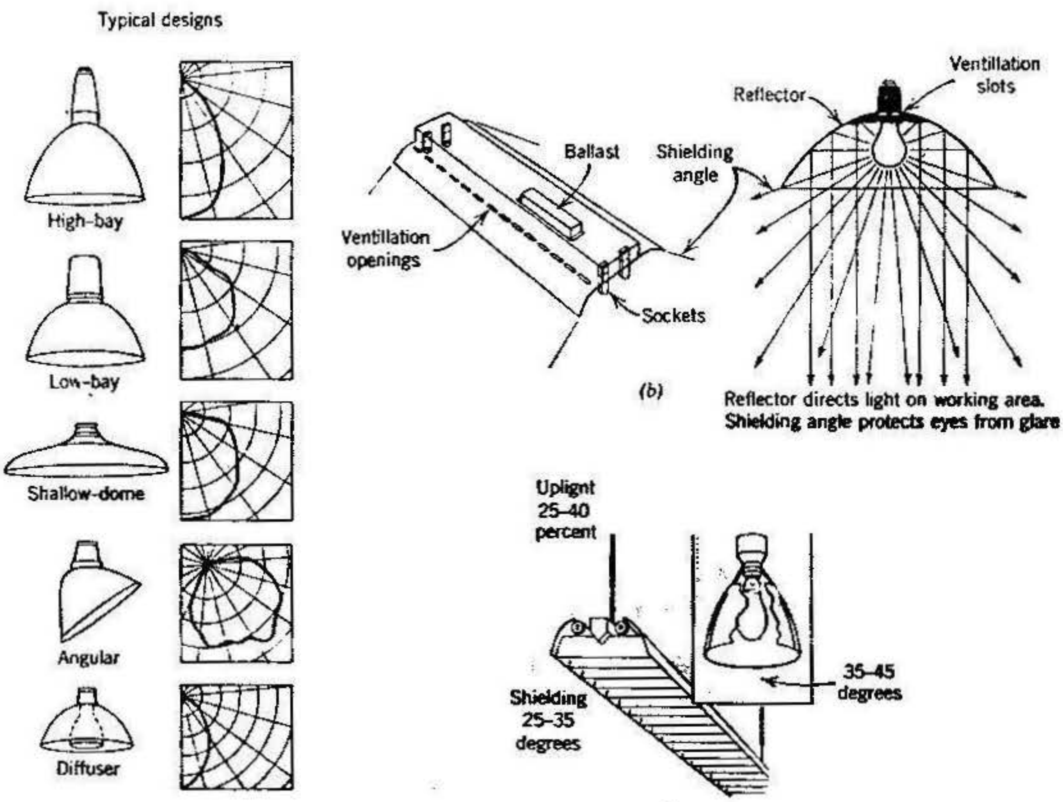


Other suggestions for lowering costs, both initial and operating, include using ventilated luminaires that tend to be self-cleaning by connection. See figure below.

In addition to giving the needed upward light component, using bus-mounted fixtures for rapid installation and repair (see figure below), using lowering mechanisms on high-bay units to avoid catwalk or platform relamping with concomitant extremely high cost, using fixtures arranged for "stick" relamping from the floor in medium-and low-bay work, and generally incorporating the most modern equipment into the plant. Typical industrial reflector fixture designs are given in this figure below.



Typical industrial reflector fixture designs are given in the figure below.



(a) (b) (c)

Proper maintainance is of paramount importance in industrial facilities because of the prevalence of dirt, vibration, and rough service: Under maintainance is subsumed cleaning, relamping, inspection, and preventive maintainance. Relamping on a burnout basis is extremely uneconomical because of disruption of production and lowered production due to lumen depreciation before burnout. Relamping is normally done on a planned group basis. Similarly, if the specific facility has a high dirt accumulation rate, cleaning must also be done on a planned group basis, rather than only at relamping time.

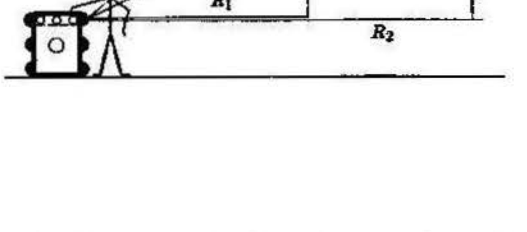
Ballast noise, including the high levels of HID ballasts, is not usually a factor in industrial facilities bacause of high ambient noise. In relatively quiet installations and/or where fluorescent fixtures are mounted a short distance above the work bench as in inspection and fine assembly, this is not true and noise ratings and conditions must be examined carefully.

Vertical-Surface Illumination

In industrial facilities more than any other, the illumination of vertical surfaces is crucial. This is a result of the nature of the work; machines, storage, gages, etc. all require high-level vertical-surface illumination. Examining the figure below, and the deviration given there, we bote that maximum vertical illumination (illumination resulting from the horizontal-lighting component) is obtained when the angle between the fixture's vertical axis and the work is approximately 35%. Hence, we should select a fixture whose candlepower distribution curve demonstrates such a characteristic most closely.

Vertical surface illumination. *The illumination on the vertical surface is the result of the horizontal component of the lighting. This is*

$$fc = \frac{cp}{D^2}\sin\theta = \frac{cp \times R}{D^3} = \frac{cp \times \cos^2\theta \sin\theta}{H^2}$$



To maximize the horizontal component, we set the derivative of FC with respect to θ, to zero. Thus

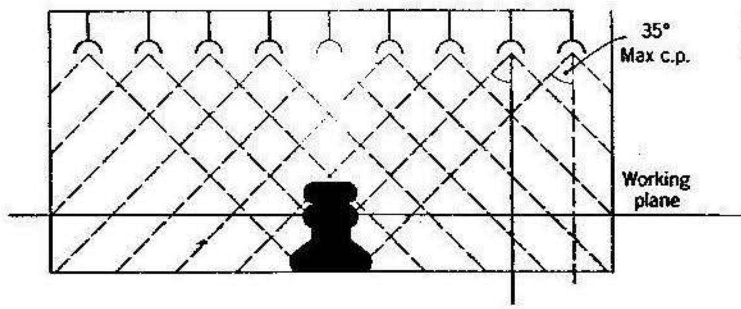
$$\frac{dfc}{d\theta} = \frac{cp}{H^2}(-2\cos\theta\sin^2\theta + \cos^3\theta) = 0$$

or

$$2\sin^2\theta = \cos^2\theta; \quad \tan^2\theta = \tfrac{1}{2};$$

$$\tan\theta = 0.707 = \frac{R}{H}; \quad \theta \cong 35^\circ$$

The fixture of the figure below shows the above's characteristic and would be a good choice. Of course, the derivation is for a single location and fixture. For good vertical and angular illumination over a large area, select a fixture as above, and arrange fixtures with considerable overlap.



Layout for good vertical surface illumination.

Special Lighting Application Topics

Emergency Lighting

Emergency lighting is required when the normal source is interrupted for any of three reasons:

1. Interruption of current flow through operation of a circuit disconnect. For example, inadvertent de-energizing of a circuit at a panel or switchboard.
2. Failure of the building's electrical system.
3. General power failure.

Systems that cover the above three situations are normally defined as follows:

Type 1 — all three situations
Type 2 — situation 2
Type 3 — situation 3

Therefore, sensors for type 1 systems are highly localized, those for type 2 less so, and those for type 3 are only at the service entrance point.

(a) **Codes**

Since this item involves safety, it is covered in various codes, all of which have jurisdiction and unfortunately not all of which agree in their requirements. The principal authorities

1. Fire and Safety Code
2. National Electric Code
3. OSHA regulations

(b) **Occupancies Requiring Emergency Lighting**

The codes require that emergency lighting be provided automatically for means of egress, in specific occupancies. These are usually taken to mean:

1. Places of assembly for 300 or more persons; type 1, 2, or 3 with more than 1000 persons; type 1.

2. Structure into which daylight does not penetrate, with occupancy of 100 persons or more: Types 1, 2, or 3.
3. All educational and institutional occupancies: Type 1 or 2.
4. Multiple residences with 25 or more dwelling units: Types 1, 2, or 3.
5. Merchandising spaces with areas greater than 3000 sq. ft. (300 sq.m.), with levels above or below the street, and those on one level that are so large that daylight will not penetrate sufficiently: Type 1 or 2.
6. Office building with occupancy in excess of 1000 persons; types 1, 2, or 3.

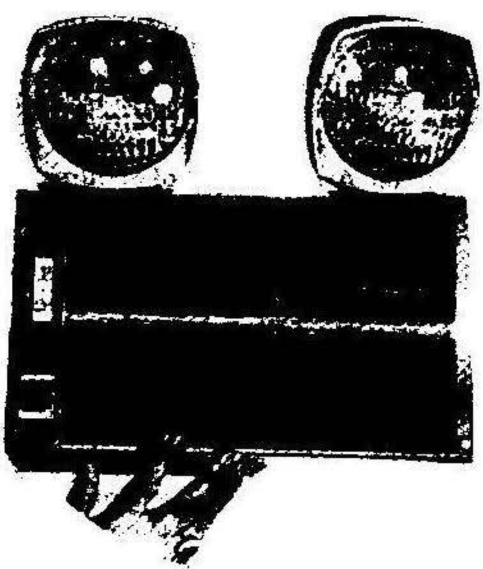
(c) **Type, Amount and Duration of Emergency Lighting**

The codes and most authorities accept 1.0 fc of illumination as sufficient to avoid panic and permit orderly egress. This level is usually understood to be the average illumination but none of the codes makes uniform coverage mandatory. This point is further discussed under equipment arrangement. Duration of emergency lighting varies with the codes, from 1/2 hour to 1 1/2 hours for egress, and up to indefinite periods (at higher levels) for facilities that cannot be evacuated. The table below give general criteria and typical recommendation for emergency lighting for egress as well as for other purposes.

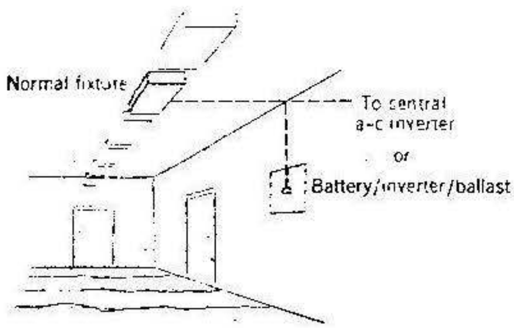
(d) **Types of Emergency Lighting Systems**

Generators supplies selected portions of the normal lighting system through special emergency-lighting panels. While central battery systems can supply a d-c distribution system or, if equipped with an inverter, can supply a-c as well. The availability of efficient inverters has practically eliminated central d-c systems. These have the added disadvantage that the incandescent fixtures they supply are not part of the normal system, and may obtrude upon the architecture, even when recessed and attractively finished. This is also true of package units spotlight-type heads (see figure below). Such units are best applied in individual rooms and isolated locations. The central battery with inverter, like the central generator, supplies lighting units that are usually (although not necessarily) part of the normal system. This arrangement has the advantages of economy, neatness, ability to use a-c sources (fluorescent), and reliability.

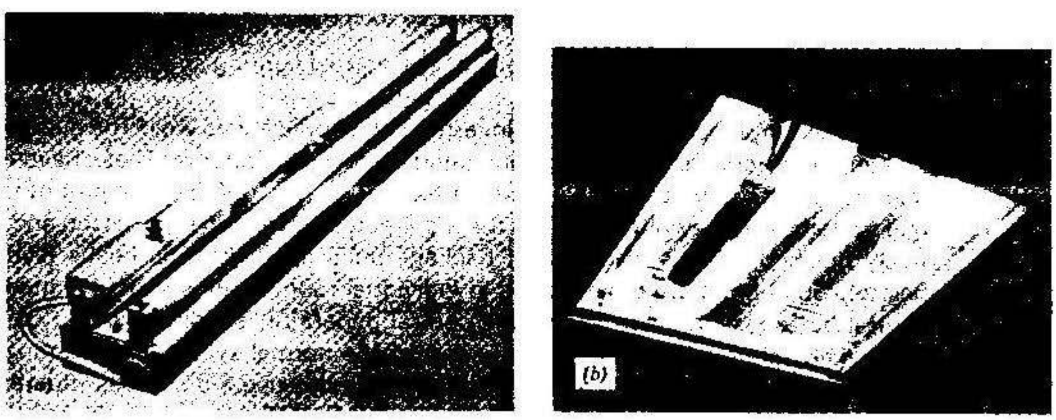

(b)



This arrangement has the advantages of economy, neatness, ability to use a-c sources (fluorescent), and reliability (see figure below). These units are usually designed to provide the 1 1/2 hours of illumination required by the code and to be completely maintainance-free for 7 to 10 years, after which the battery is simply replaced. Since high temperatures seriously affect battery life, it is advisable to mount these integral packages in a location other than that occupied by the fixture ballast. (See second figure).



The use of an integral or remote (shown) concealed battery/inverter allows instantaneous emergency lighting of areas blacked out by local or general power failure. The use of fluorescent sources provides seven times the illumination possible with incandescent, for the same battery size.



A cylindrical design containing battery, charger-inverter, and controls is mounted in the lamp section of the fixture, thereby avoiding exposure to the high temperatures of the ballast compartment. The illustrated unit can be mounted in tandem with a 36-in. lamp, replacing a 48-in. lamp as in (a). The 3-ft lamp is activated during normal and emergency operation. Alternatively , the unit can be mounted between the lamps as in (b).

(e) Arrangement of Fixtures

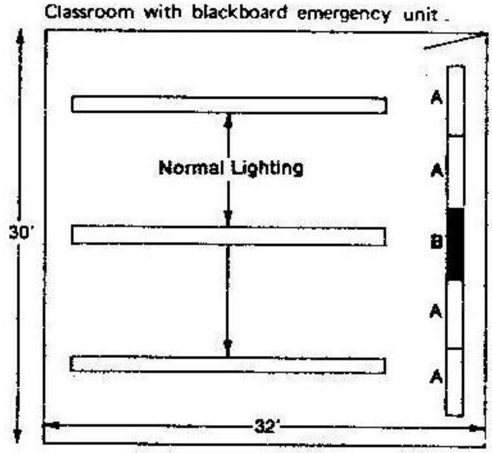
When the illumination level in an interior space drops sharply from a level of 30 to 150fc to 1.0fc. the eyes require up to 5 minutes to fully accomodate. During this long period the space's occupants are essentially sightless — a condition that lends itself readily to panic. For this reason, we recommend that the emergency lighting units be designed to give 1.0 fc uniform, not average, illumination. The difference is that the latter can be accomplished with bright, spotlight-type heads which, unless carefully arranged, can create disabling glare, distorting shadows, and impede eye accomodation. In such an event they do little to fulfill their primary function. A requirement for uniform illumination will normally result in a design using selected normal fixtures or lamps within such fixtures. This will result in altering only the level of lighting during a power failure — not the quality. This allows the eye to adapt rapidly

eliminates disabling glare, and assists in creating the atmosphere necessary for orderly, safe egress. (See figure below).

Emergency Operation—every 7th unit 28' on center provide 1 FC minimum.

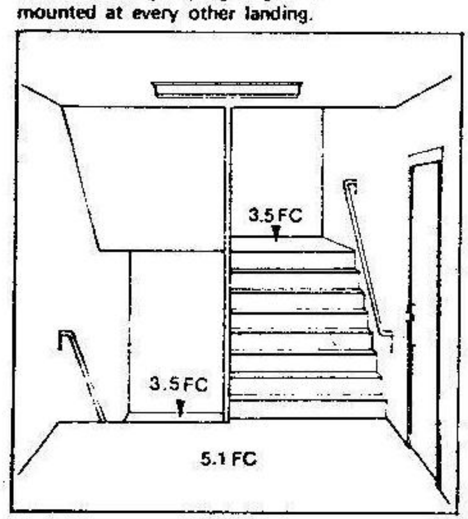
(a)

Classroom with blackboard emergency unit.



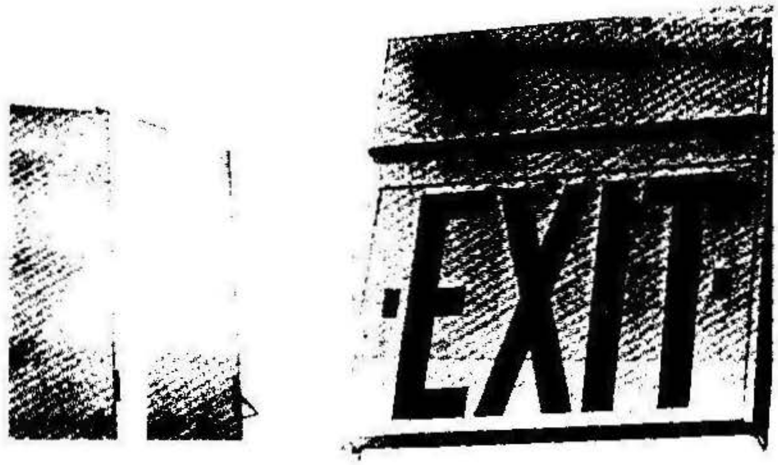
(b)

Stairwell emergency lighting unit mounted at every other landing.



(c)

Similarly, all exits must obviously be well illuminated so that traffic will flow smoothly. The well-known exit sign can also be equipped with an integral battery and control equipment to illuminate itself (normally with incandescent lamps) and the area immediately below it. (See these figure below).

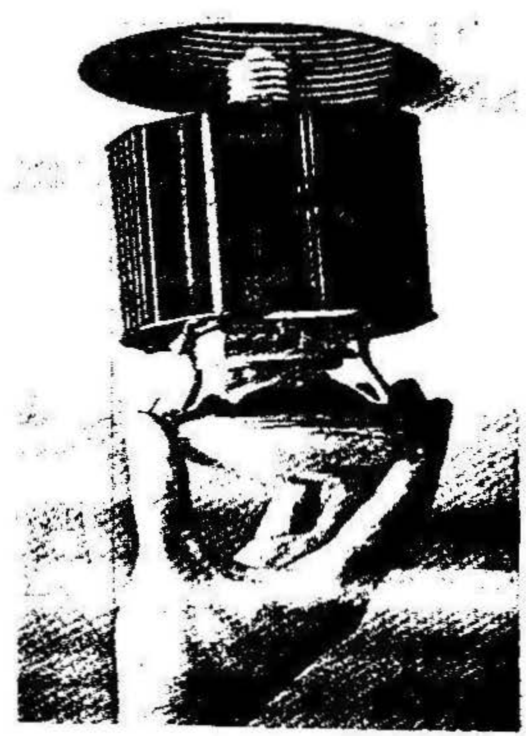


Building Retrofit

Existing building lighting systems can be modified to increase efficiency, decrease glare, and decrease energy consumption by applying the procedures, techniques, and knowledge gained in the last four chapters.

(a) **Sources**

1. Replace standard fluorescent tubes with low-energy units.
2. Replace continuous burning incandescent sources with high-efficacy fluorescent sources or HID (see figure)



3. Replace general service incandescent lamps in downlights with lower wattage, R, PAR, or elliptical reflector lamps.
4. Replace existing HID sources with higher-efficacy HID units such as HPS and metal-halide. Use those that can be operated on mercury-lamp ballasts, to avoid the cost of ballast replacement.
5. Increase daylight-use add reflectors to increase penetration.

(b) **Fixtures**

1. Replace diffusers with more efficient ones-reduce glare, increase CRF and ESI footcandles; this will permit reducing lighting levels.
2. Install multilevel ballasts.
3. Add two-level control to HID units.
4. Institute a program of maintainance that will permit decreasing energy use by at least 20% while maintaining output.
5. Modify fixture locations to give minimum direct and reflected glare.
6. Add task lighting.
7. Reduce overall lighting to apropriate ambient level by fixture removal.

(c) **Other**

1. After making the above adjustment check that levels do not exceed recommendations. Reduce levels by removing two of four lamps in a fixture. Also remove the associated ballast with two-lamp fixtures, remove one tube and replace with a dummy tube if the ballast will be adversely affected by one-lamp operation.
2. Rearrange tasks so that the most difficult ones benefit most from daylight.
3. Install low voltage or sonic switching to give requisite local light control.
4. Repaint to give requisite reflectances.
5. Install time switches to automatically coordinate lighting with tasks and time, for example, reduce lighting during lunch.
6. Operate closet lights with door switches.
7. Install pilot lights outside storage rooms to indicate lighting "on".

Floodlighting

Floodlighting, both interior and exterior, is extensively used for such diverse locations as are listed in the table in the next page, in addition to the more common sports lighting, which is not listed. At the designer's disposal are a variety of sources with respect to output, color, life, efficiency, and wattage (See chapter 13).

Lighting Application Guide

Application	Minimum Footcandles Maintained*	Watts Per Square Foot Generally Required			
		Tungsten Halogen	Mercury Units	Metal-Halide	High-Pressure Sodium
Automobile Parking					
Attendant parking	2	0.38	0.17	0.11	0.075
Industrial lots	1	0.13–0.15	0.06–0.07	0.037–0.044	0.026–0.03
Self-parking lots	1	0.13–0.15	0.06–0.07	0.037–0.044	0.026–0.03
Shopping Centers					
Neighborhood	1	0.13–0.19	0.06–0.09	0.037–0.055	0.026–0.038
Average commercial	2	0.26–0.3	0.12–0.135	0.075–0.087	0.052–0.06
Heavy traffic	5	0.65	0.29	0.19	0.13
Automobile Sales Lots					
Front row (Front 20 ft)	50	10.	4.5	2.9	2.0
Remainder	10	1.5–1.8	0.68–0.81	0.44–0.52	0.3–0.36
Building					
Construction	10	1.5–1.8	0.68–0.81	0.44–0.52	0.3–0.36
Excavation	2	0.26–0.3	0.12–0.14	0.075–0.09	0.052–0.06
Buildings up to 50 ft High	**Adj. Area** Light / Dark				
Light surfaces	15 / 5	3.3 / 1.2	1.5 / 0.54	0.96 / 0.35	0.66 / 0.24
Medium light	20 / 10	4.3 / 2.2	1.94 / 1.0	1.25 / 0.64	0.86 / 0.44
Dark surfaces	50 / 20	10.0 / 4.3	4.5 / 1.94	2.9 / 1.25	2.0 / 0.86
Billboards and Signs	**Adj. Area** Light / Dark				
Good contrast	50 / 20	10.0 / 4.3	4.5 / 1.94	2.9 / 1.25	2.0 / 0.86
Poor contrast	100 / 50	20.0 / 10.0	9.0 / 4.5	5.8 / 2.9	4.0 / 2.0
Protective Lighting					
Gates and vital area	5	1.2	0.54	0.35	0.24
Building surrounds	1	0.15–0.19	0.07–0.09	0.044–0.055	0.03–0.04
Roadways					
Along buildings	1	0.24	0.11	0.07	0.05
Open areas	0.5	0.08–0.1	0.036–0.045	0.023–0.029	0.02
Storage yards (active)	20	3.6–4.3	1.6–1.94	1.04–1.25	0.72–0.86
Storage yards (inactive)	1	0.15–0.19	0.07–0.09	0.044–0.055	0.03–0.04
Shopping Centers					
Parking areas (attraction)	5	0.65	0.29	0.19	0.13
Buildings (attraction)			(See Buildings)		
Used Car Lots*			(See Automobile Parking)		

*All footcandle levels for ground area applications are *horizontal* values.

Although a detailed floodlighting design involves complex calculations beyond the scope of this work, it is often sufficient for the designer to utilize a watts per square foot table such as the table in the page in order to determine the approximate floodlighting requirements.

Thus, if one is concerned with lighting a self-service parking lot at a neighborhood shopping center, and metal-halide is selected, the table tells us that approximately 0.055 w/sq. ft. will suffice. If the lot is 200 x 500 ft. or 100,000 sq. ft. (66 x 165 m or 10,000 sq. ±), then 0.055 x 100,000 = 5,500 w are required.

Lighting Application Guide

Application	Minimum Footcandles Maintained*	Watts Per Square Foot Generally Required			
		Tungsten Halogen	*Mercury Units*	*Metal-Halide*	*High-Pressure Sodium*
Automobile Parking					
Attendant parking	2	0.38	0.17	0.11	0.075
Industrial lots	1	0.13–0.15	0.06–0.07	0.037–0.044	0.026–0.03
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Shopping Centers					
Neighborhood	1	0.13–0.19	0.06–0.09	0.037–0.055	0.026–0.038
Average commercial	2	0.26–0.3	0.12–0.135	0.075–0.087	0.052–0.06
Heavy traffic	5	0.65	0.29	0.19	0.13
Automobile Sales Lots					
Front row (Front 20 ft)	50	10.	4.5	2.9	2.0
Remainder	10	1.5–1.8	0.68–0.81	0.44–0.52	0.3–0.36
Building					
Construction	10	1.5–1.8	0.68–0.81	0.44–0.52	0.3–0.36
Excavation	2	0.26–0.3	0.12–0.14	0.075–0.09	0.052–0.06
Buildings up to 50 ft High	*Adj. Area* *Light Dark*				
Light surfaces	15 5	3.3 1.2	1.5 0.54	0.96 0.35	0.66 0.24
Medium light	20 10	4.3 2.2	1.94 1.0	1.25 0.64	0.86 0.44
Dark surfaces	50 20	10.0 4.3	4.5 1.94	2.9 1.25	2.0 0.86
Billboards and Signs	*Adj. Area* *Light Dark*				
Good contrast	50 20	10.0 4.3	4.5 1.94	2.9 1.25	2.0 0.86
Poor contrast	100 50	20.0 10.0	9.0 4.5	5.8 2.9	4.0 2.0
Protective Lighting					
Gates and vital area	5	1.2	0.54	0.35	0.24
Building surrounds	1	0.15–0.19	0.07–0.09	0.044–0.055	0.03–0.04
Roadways					
Along buildings	1	0.24	0.11	0.07	0.05
Open areas	0.5	0.08–0.1	0.036–0.045	0.023–0.029	0.02
Storage yards (active)	20	3.6–4.3	1.6–1.94	1.04–1.25	0.72–0.86
Storage yards (inactive)	1	0.15–0.19	0.07–0.09	0.044–0.055	0.03–0.04
Shopping Centers					
Parking areas (attraction)	5	0.65	0.29	0.19	0.13
Buildings (attraction)			(See Buildings)		
Used Car Lots			(See Automobile Parking)		

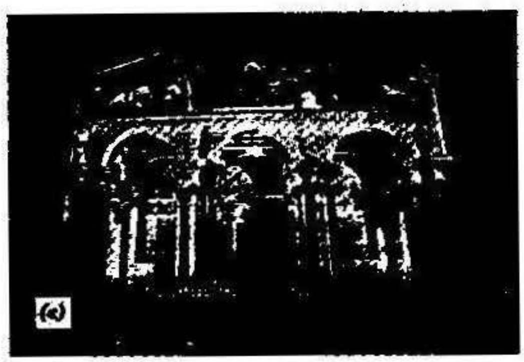
*All footcandle levels for ground area applications are *horizontal* values.

Arrangement and choice of equipment remains then, before the problem can be considered solved. Considerable assistance on this score can be obtained from either the lighting engineer involved or from representatives of the equipment manufacturers.

Although most floodlight installations use a single type, the installation of the figure in the next page used a combination of metal-halide and HPS to obtain the desired effect.

(a) *The Statue of Liberty was relighted for the American Bicentennial. It was found that 58- 1000 watt metal halide units give 40 to 50 fc of white light on the statue. Eleven 400-w HPS units were selected to compliment the color of the granite base, which they light to 10 fc.*

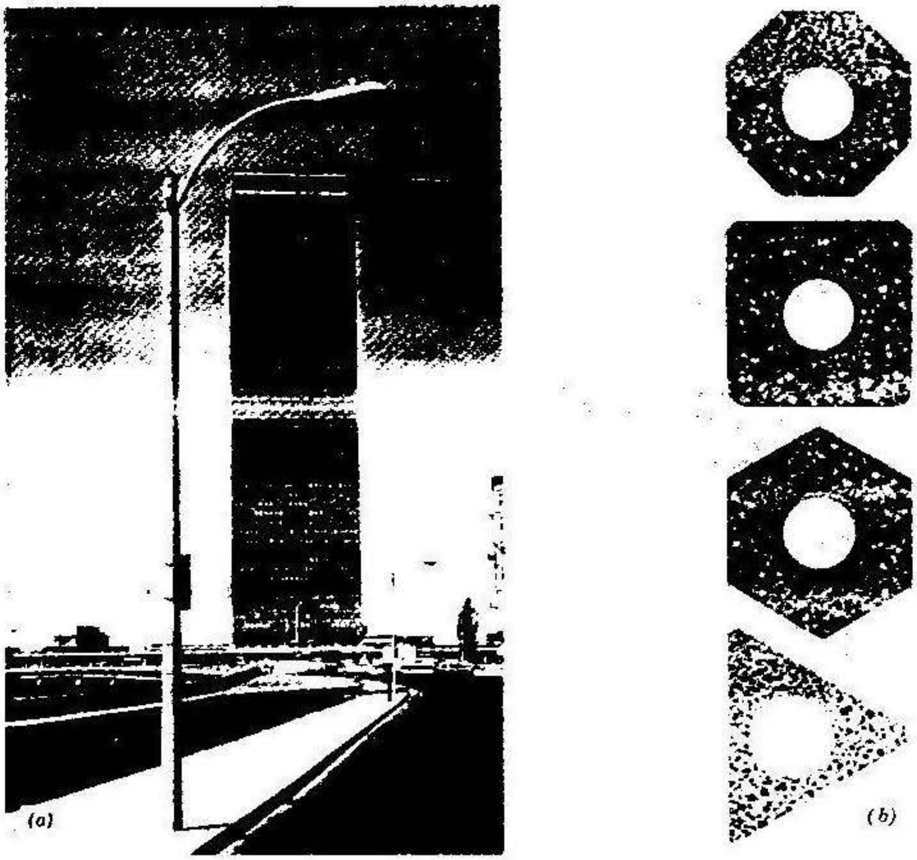
(b) *Floodlighted section of wall surrounding the Old City of Jerusalem, Israel, adjacent to the Jaffa gate. Light sources are 400-w, high-pressure sodium units, giving an average illumination level of 50 lux.*

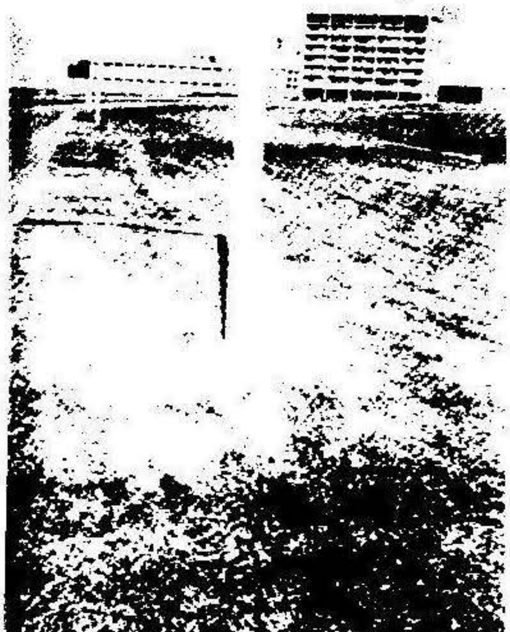


(c) *Church of All Nations, Mount of Olives, Jerusalem, Israel. Floodlight sources are 250- and 400-watt mercury and metal-halide units, giving an average illumination of 70 lux. Sources were selected to compliment the colors in the mosaic at the top of the facade.*

Street Lighting

Although detailed street-lighting calculations and design considerations are beyond our scope, a few remarks are in order. New installations now use HID sources almost exclusively (High Intensity Discharge lamps like high pressure sodium (HPS) lamps). The low efficacy and short life of incandescent sources and the bulkiness of fluorescents make them obsolete. Furthermore, high street-lighting levels reduce vandalism and crime, improve night merchandizing, and add to an area's attractiveness. Some typical designs of street lighttng and other outside luminaires are shown in these figures.

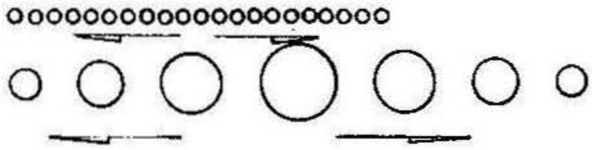

(a)
(b)



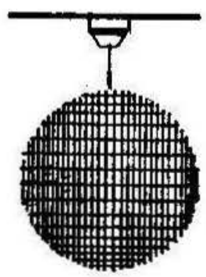
(a)

(b)

DISCO LIGHTING

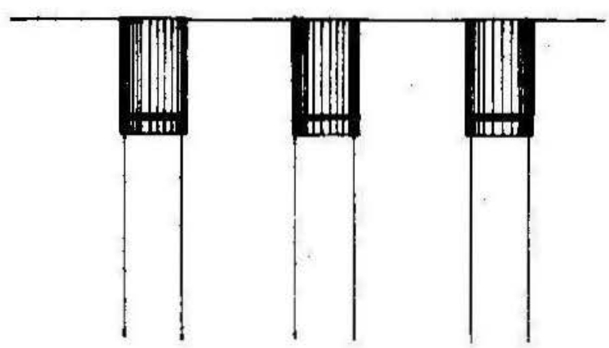


MOVING LIGHTS
THE LIGHT IS DESIGNED TO MOVE RIGHT TO LEFT OR LEFT TO RIGHT (PROGRAMMED WITH SPECIAL TIMERS)

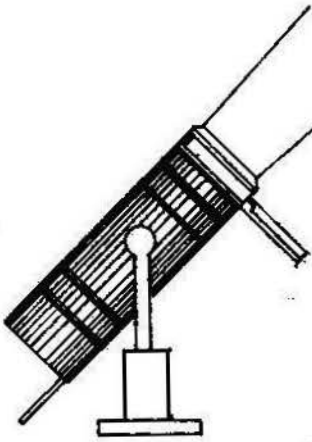


a Mirror Ball

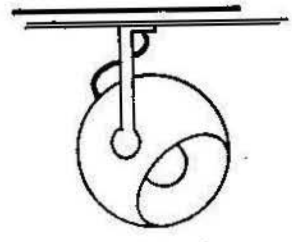
REFLECTOR (GLOBE SHAPE)
A SPARKLING BALL REFLECTING ITS LIGHT WHEN BEAMED UPON BY SPOT LIGHTS; THE BALL ROTATES TO GIVE A MOVING BACKGROUND

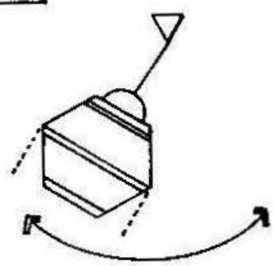


RAIN LIGHTS
AN ARRANGEMENT OF LIGHTS WHICH IS LIKENED TO A PIN LIGHT AND HAS STRAIGHT CONCENTRATED BEAM.



SPOT LIGHT
THIS LIGHT CONCENTRATES ON AN OBJECT OR A HUMAN / PEOPLE DANCING SHOWING AND EMPHASIZING TO A ONE SUBJECT

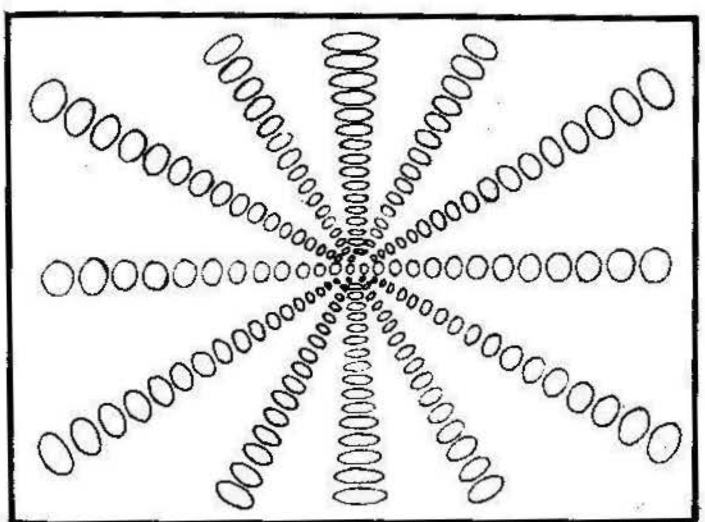




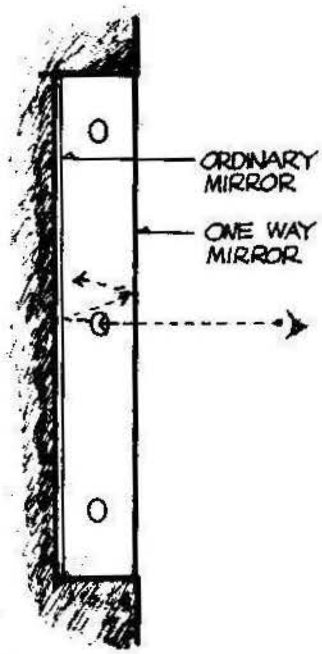
TRACK LIGHT-
LIGHT CONNECTED TO A TRACK AND CAN BE ARRANGED

STROBE LIGHT
THIS PRODUCES A THROBBING, FLICKERING FLASHING BRIGHT LIGHT THAT PRODUCES AN EFFECT THAT DANCERS DANCE FASTER THAN NORMAL SPEED.

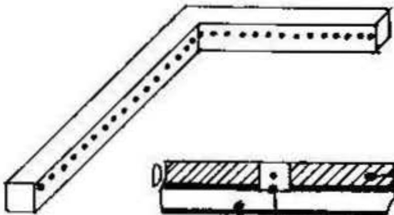
INFINITY LIGHT



THIS IS AN EFFECT OF DEPTH AND DISTANCE



THE DESIGN IS ONLY A SET OF BULBS (1) IN A GLASS HOUSING 0.15 THK ±, THE BACKGROUND IS A MIRROR AND THE FOREGROUND IS A ONE WAY MIRROR - THE PEOPLE CAN SEE INSIDE, HOWEVER LOOKING SO THE BULB IS REFLECTED TO THE MIRROR WHICH IN TURN IS TURNED TO THE ONE-WAY MIRROR

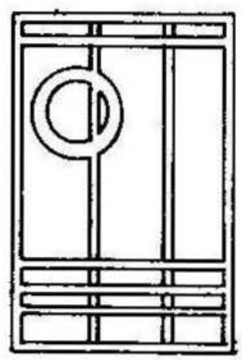


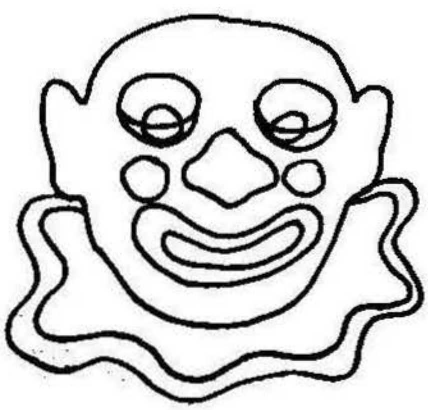
TIVOLI LIGHTS
ONE INCH SQUARE HARD PLASTIC WITH SMALL RUNNING LIGHTS INSIDE CAN BE USED TO LINE THE DANCING FLOOR.

SECTION

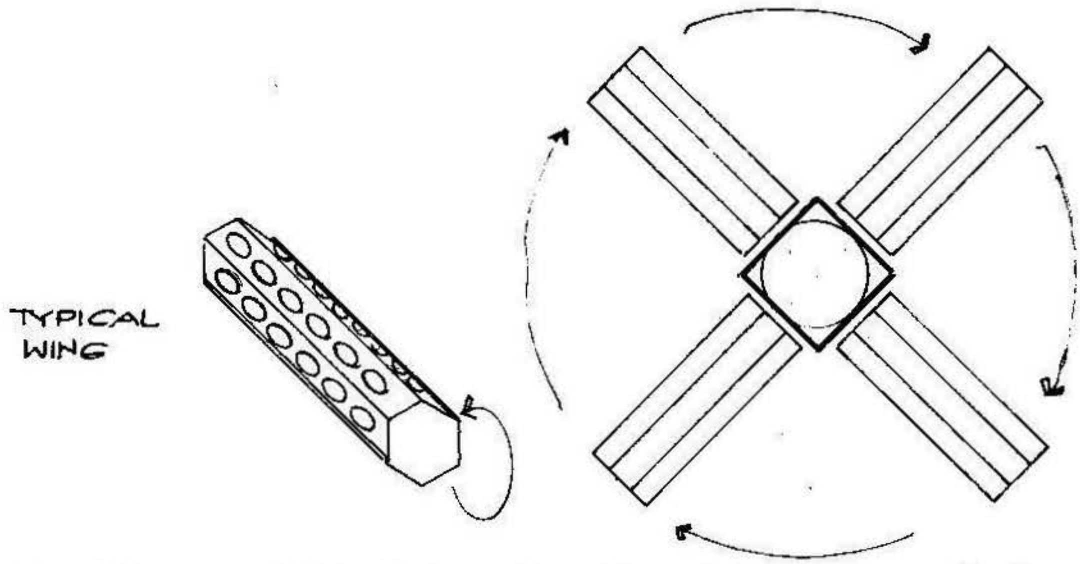
NEON LIGHT-MOUNTED ON WALL ON MIRRORED CIELING

NEON LIGHT IS A TUBE FILLED WITH NEON GAS

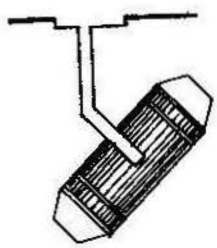




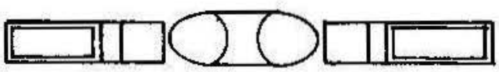
LASER LIGHT - A NEW METHOD OF DISCO LIGHTING ITS SPECIAL FEATURE IS THAT IT CAN OUTLINE ANY FIGURE IN THE OPEN AIR SOMETIMES WITH THE HELP OF A FOG MACHINE



CEILING FAN LIGHT - ROTATES LIKE A FAN AT A REGULATED SPEED; MOUNTED ON EACH WING ARE LIGHTS OF DIFFERENT COLORS.



BLACK LIGHT
PRODUCES AN EERIE EFFECT AND CHANGES TRUE COLORS AND USUALLY MAKES A PERSONS TEETH LUMINOUS



POLICE SIREN - IS A DUPLICATE OF THE LOCAL POLICE PATROL CAR; IT IS USED WHEN THE SIREN IS SOUNDED AND IS DUBBED FOR EFFECT

LIGHTING/SUMMARY

Good light and good lighting, the one natural and the other man-made, are as central to the success of any room as they are to sight, and yet curiously, they are often the least planned, the least thought-about of all domestic ingredients — very much the afterthought, in fact. It is odd, for after all a mass of daylight is one of the few free assets anyone is likely to get with a home and should be de the most of — enhance, filtered, or allowed to flow to the best of one's ability. Artificial lighting, on the other hand, is certainly the most flexible way to change mood, atmosphere, or feeling, and will exaggerate space or diminish faults at the flick of a switch or the turn of a dimmer. Unconsidered lighting can make an otherwise exemplary room look dreary, whereas imaginative lighting can imbue the simplest ingredients with a near-mystic excitement — almost as if they had never really been contemplated before.

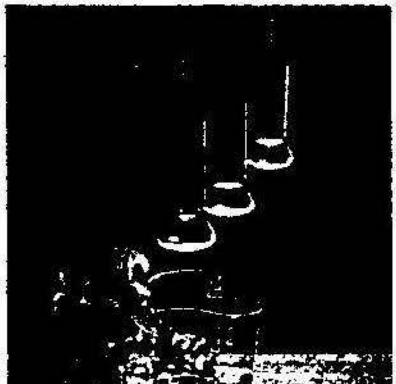
Ideally, architects should give the same amount of thought to the planning and placing of lighting equipment as they give to the proportions of windows and their treatment. But then, everybody should have the same concern for artificial light as they do for daylight. More, perhaps, because it can be controlled and manipulated at will that there is not the same concern — that there is often a failure to make the most of even the daylight that is given — seems such a waste.

The reason for this disregard — at least as far as artificial lighting is concerned — is mostly, that many people tend to light their homes as their forebears did, though with electricity instead of oil, candles, or rushlights. They seem unaware that artificial lighting has developed from being a poor daylight substitute to the point where its potential has a fundamental influence on design. When they think of lighting, they think of lights, or lamps, the actual fixtures, rather than how to manipulate the stuff. When they buy fixtures, they buy them very often for their shapes and looks but neglect to find out about their effect.

Even when they are searching out the more sophisticated lighting in a store or in a catalogue — the spots and wallwashers, the downlights and uplights — they mostly buy for looks rather than for what those looks will achieve.

And it is difficult to display the effects of lighting anywhere except in a showroom devoted to nothing else. How could it be possible to show how the position, color, and intensity of light sources will give definition to various spaces in a house; to display light and shade, strength and subtlety, in a cramped area full of dozens of different fixtures crammed together for maximum choice?

Whenever possible, if only to get an enlightened view of current techniques, it is wise to visit proper lighting showroom. If it is not possible, take careful note of pleasing lighting in other people's houses, restaurants, museums, and galleries — anywhere and anything that seems translatable into a domestic setting. For reference, here is a summary of the choice of lighting generally available.



TYPES OF LIGHTING

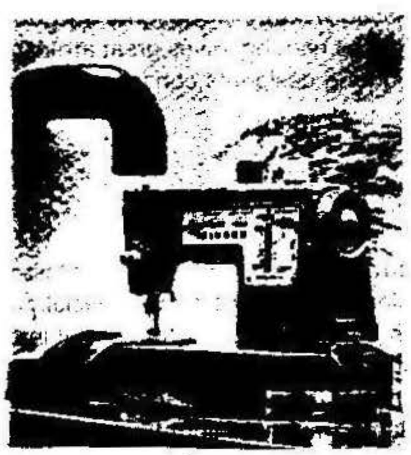
There are basically four different types of domestic lighting equipment — six, if you count the most subtle but the least effective for seeing, candlelights, spotlights, and floodlights, which have all been adapted from theatrical and industrial lighting; conventional ceiling lights, wall lights, table lamps, floor lamps, and strip lights; fluorescent lighting, and the more ambitious lighting equipment that makes light a decoration or an architectural element in itself. This last will be dealt with separately later.

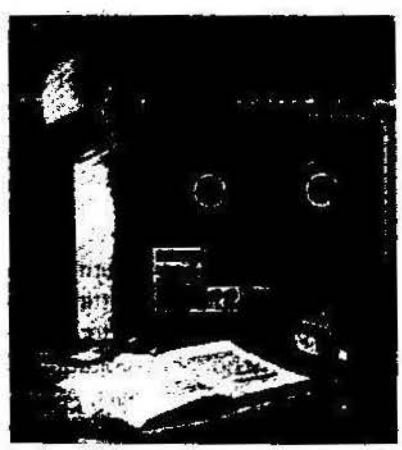
Downlights

Downlights are just that: round or square metal canisters that can be recessed into a ceiling, semi-recessed, or ceiling-mounted to cast pools of light on the ground or any surface below them.

The kind of pool of light depends on whether the bulb inside is a spot, a floodlight, or an ordinary bulb. A spot will throw a concentrated circle of light, which is at its most effective bearing down on a plant, or a bowl of flowers, or a collection of glasses as on a dining table. A floodlight will give a wider, less intense, cone-shaped light, and an ordinary bulb will provide soft over-all lighting.

Most downlight are fitted with some sort of antiglare device, and some of them are half-silvered to give a directional light. Some types can be used for wallwashing and some for pinpointing. By wallwashing, It is meant literally bathing a wall with light. Angled close to a wall of paintings, wallwashers will splash light onto the varying surfaces, leaving contrasting shadows in between. Or they will simply make a color more brilliant or a molding more effective.





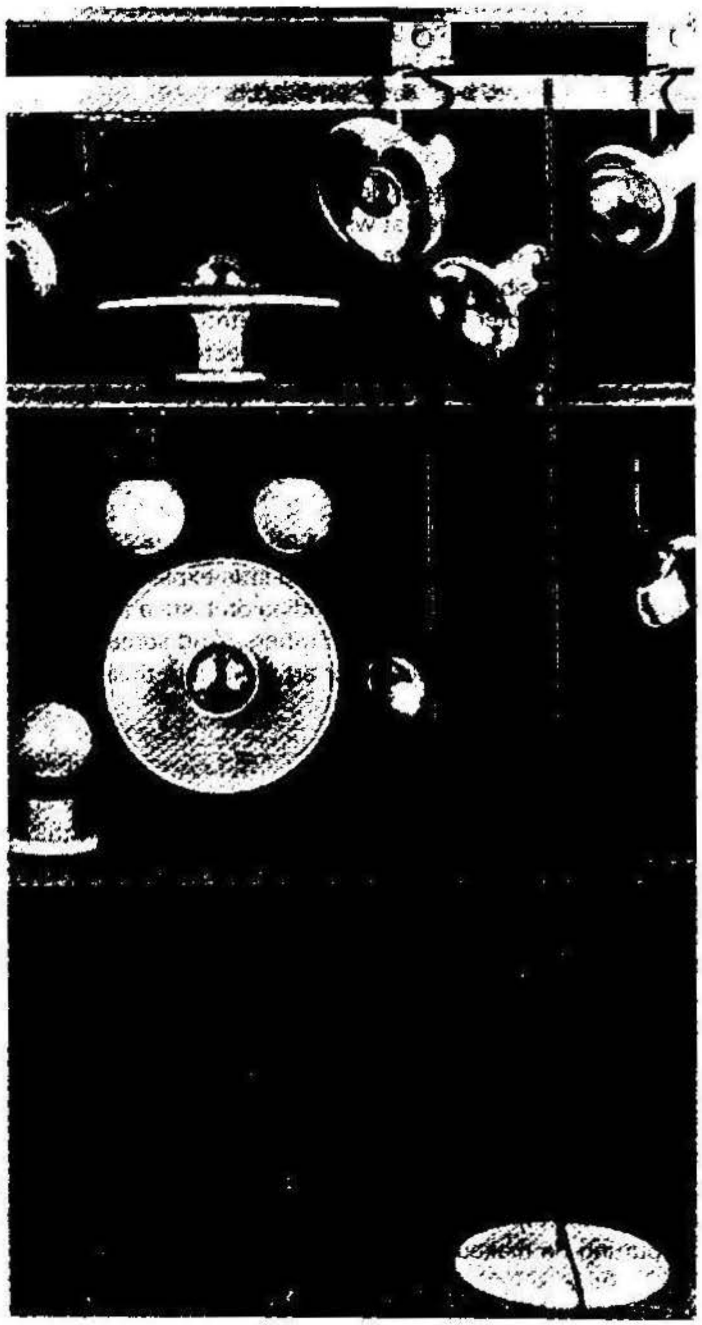
Uplights

Uplights are downlights in reverse, round or square metal canisters in different diameters, which will hold varying intensities of bulbs. Put them on the floor, under glass shelves, behind sofas, behind plants, and in corners, and they will give a beautiful, dramatic accent light, bouncing reflected light off ceilings and into the room, creating shadows and moods that could never be imagined by day. A well-placed mixture of uplights and downlights, judiciously bolstered by pin-pointing spots and light to read by, gives great atmosphere to a room, as well as the sort of reflected light that lighting designers consider the best since it gives the least glare.

Spotlights

Spots are used for accent lighting and to give strong, direct light. The simplest spotlight consists of a reflector fitting that will take an ordinary bulb. Others take specially designed spot bulbs which are often internally silvered with built-in reflectors for special intensity. A third variety hold low-voltage transformers to cast especially narrow beams on small objects or narrowly defined areas. Although normally the hotter the wire or filament, the brighter the light, a low-voltage transformer will produce the same amount of light from a lower-wattage bulb, so that in this case the lower heat makes it possible to have brighter light. There are also eyeball or framing spots for the specific lighting of paintings or objects.

Most spotlights can be mounted straight into the ceiling, onto walls, or onto tracks and pointed at anything that would benefit from special illumination. Some small spots have a magnetic backplate so that they can be attached to any surface and pointed in any direction. These are useful for concealing on the sides of bookcases or in wall recesses or ceiling angles to give extra accent. Even smaller free-standing eyeball spots or miniature free-standing high-intensity, low-voltage spots can be pushed in among books or objects on shelves to give more pools of light and shade. These eyeball spots can also be recessed in the ceiling.



Tracks are an excellent way of getting a lot of light from one outlet without extra and expensive electrical work (as well as the making good afterwards that such work generally entails). Mount them on or recess them into a ceiling or down the side of a wall. Arrange them in lines or rectangles or squares or circles a few feet out from the edge of the room, or straight down the middle. On them go spotlights or floodlights, which — ever seem best for the purpose, or a mixture of both that can be angled at will. Some of the more sophisticated varieties contain multicircuit systems to allow even greater flexibility of control. Plug-mold strip is another variation and comes in a variety of lengths. It can run around the edge of a room behind a concealing baffle or pelmet of some sort. It will take any variety of bulb with the use of a socket adapter, and bulbs can be plugged in at 6-inch intervals for varying effects, but it is particularly good for wallwashing. Plug-mold strips can also be mounted on shelves and covered with opal acrylic or frosted glass, or used as ribbons of light in much the same way at the base of a seating platform. Lyte Trim, a miniature track with miniature spots, is also extremely useful for shelves, bedheads, and so on.

It is particularly important for spots or floodlights to be used in conjunction with dimmers so that their intensity can be controlled at will; besides, dimmers both save energy and prolong the life of the bulbs. Most dimmers are combined with an on/off switch and can be installed quite easily. If it is impossible to rewire a room for one reason or another, a dimmer plug, which is a little like an adapter, can be used to control a couple of fixtures. Unlike a regular dimmer, however, a dimmer plug uses as much electricity as any ordinary fixture.

Conventional Lights

Conventional lights and lamps of this sort need little explanation and there is an enormous choice of shapes, color, and materials, depending on taste and space and pocket. But some are more suitable for certain purposes than others. And some, such as those Italian snaky coils of light, are like pieces of sculpture or art objects in their own right, quite apart from their light-throwing qualities.

Pendant fixtures are ubiquitous, but they tend to flatten shadows and do not give enough light by which to read or work comfortably. The amount of light they let out depends very much on the type of shade used and the height at which they are hung. Directional pendants, which are good over dining tables and sometimes over side tables, have opaque shades so that the light shines downward. The shade should be deep enough to prevent light shining into eyes, and the pendant is best mounted on a rise — and — fall fixture. Ceiling-mounted lights give good over-all general light, but it looks flat unless this general source is used in conjunction with other types of light.

If wall lights are used, or have to have to be used because that is the way a space has been wired, they are best if they are directional and used to bounce light off a ceiling or off the wall itself, or to light an object, picture, or surface. Other wall fittings, such as bare bulbs placed at the side or the top of a mirror as in a theater dressing room, given an exceptionally good light for putting on makeup or shaving.

Table lamps are meant to provide concentrated areas of light. Again depending on the type of shade, they will bounce light up or down or spread it horizontally. Directional desk and table lamps for working by should be adjustable and let the light shine down on the paper or work in question.

Floor lamps give general or directional light depending on type and shade, and the variety fitted with spots can be a good substitute for spots or track. They make useful reading lights and can be moved around, set to shine on a book — preferably over the left shoulder — or directed onto a wall or ceiling. When choosing shades, remember that translucent silk shades are the best light diffusers, followed by linen and paper.

Strip lights of the incandescent variety, as opposed to fluorescent tubes, are useful for concealed lighting when they are put behind a baffle or pelmet to shine down on shelves in an alcove, or to light up curtains or a working surface.

Fluorescent Lighting

Fluorescent tubes, either straight or circular, give about three times as much light as a tungsten or filament bulb of the same wattage and have an average life of 5,000 hours. They are therefore, a good deal more economical to use where high levels of light are needed for long periods at a time. In fact, for maximum efficiency these lights should be switch on and off as little as possible. The tubes are best masked by a baffle of some sort, or by a panel of milky plexiglass or Perspex.

Because fluorescent light can distort color, it is important to choose the right color tube for a particular area. If tungsten and fluorescent are to be used together, for example, "de luxe warm white" is the nearest in feeling to tungsten light and when diffused is useful for kit-

chens and bathrooms. "De luxe natural" gives reasonable color quality, is tolerably warm, and is quite good for kitchens, but because it dramatizes color, it is not so good in bathrooms. Used with discretion, a little can be mixed with candlelight for dining in a working kitchen. "Plain natural" simulates daylight and can be used as a booster when daylight lacks luster or penetration. But tubes sold with names like "warm white" (without the "de luxe"), "cool white," and "daylight" emphasize greens and yellows and skill pinks.

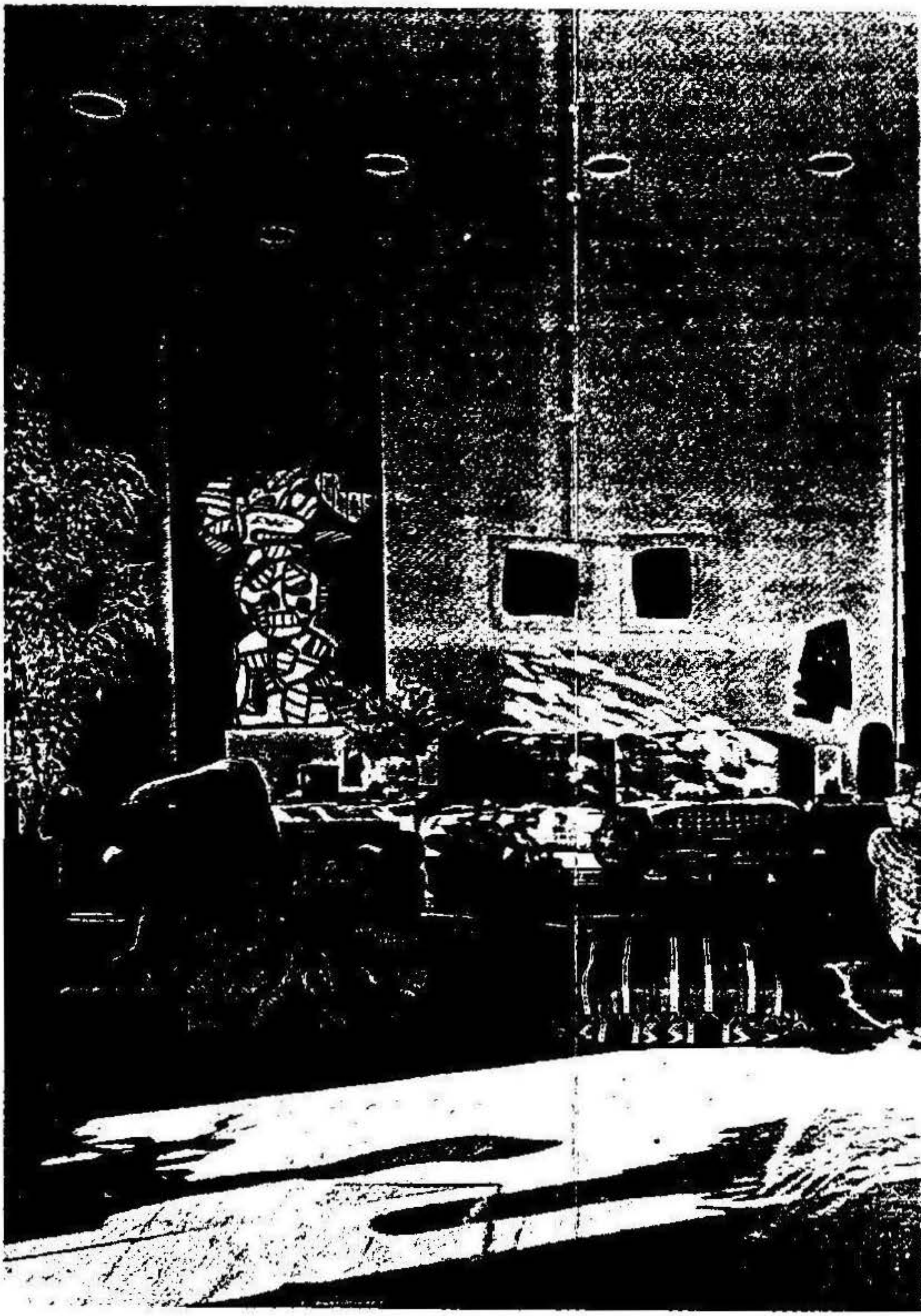
Useful Principles

The most common lighting problem is how to improve the light in existing houses, especially when there is no lighting consultant on hand to give advice. Unles there is already a well-planned electrical layout that provides for all kinds of lighting, or an enormous number of electrical outlets — both of which are desirable but unlikely — the choice is either to add new outlets to existing circuits (which is best, but expensive) or to install lengths of lighting track, which can take a variety of extra fittings, to the odd ceiling outlets that are in place already. If there are no ceiling outlets, make do with the kind of floor lamps that carry adjustable spots. If major rewiring is proposed, it should be planned in detail before the electrician starts work and completed before any decorating is begun.

In any event, whatever the circumstances and the problems, it is useful to know something about the principles behind modern lighting design. I have divided them into the practical considerations (making the most of daylight; what works best where; the comfort the safety factor) and the decorative aspects (what works best with the structure of the place; what works best with paintings, objects, and texture, and the effect of light on color and vice versa).

Making the Most of Daylight

Although many people tend to think of artificial light as the counterfeit of daylight and the two as separate issues, an effective lighting system which will provide comfortable light at all times means that a balance must be struck between the two, the one discreetly boosting the other when necessary. To do this successfully it is important to understand the limitations of daylight as well as its qualities. It has, of course, all the advantages of variety: variety in intensity, in almost hourly as well as seasonal changes; and variety in color, from intense blue to overcast grey, from the clear light of early morning to the bluish dusk of evening, from the burnished light of high summer to the bright white cast up by snow. During each phase the interior of a building will look subtly different. That is why small windows should be left as uncluttered as possible to make the best of what light there is, why large windows should have screens or shades or blinds or nets that can filter any superabundance, and why it is useful to see a room in as many different lights as possible before deciding on a color scheme and furnishings.



However, it ought to be remembered that daylight does not have great qualities of penetration, although the low angle of the sun is winter gives deeper penetration at certain times of day than in summer. In most average rooms about 1 percent of the available daylight outside will reach the parts of the space furthest from the window, as opposed to as much as 10 percent near the window. In rooms with windows at both enos, light will fall off towards the middle. For large periods of the year, demanding visual tasks like reading, writing, drawing, or sewing can only be done close to a window, and many rooms in buildings with a narrow frontage, or in buildings surrounded by other buildings, will have poor lighting at all times of the day. This means that a good many rooms will always need the boost of artificial lighting for some purposes, and that many dark central areas in deep buildings usef for service rooms such as kitches, bathrooms, and storerooms, as well as halls and passageways, will need constant artificial light.

Again, this raises its own problems, for during the day the eye will have become so adapted to the high level of natural light, either from outside or from bright rooms, that in order to remain comfortable in dark inner areas it will require an equally high level of electric light. That is to say, a higher level than is usual at night, when the eye will have adapted again to the lower normal levels of artificial light all around. This means that ideally — and I stress *ideally* — there should be either a separate lighting system for perpetually dark rooms with a separate day night switch, or some form of dimmer control on the existing system whereby the level of light can be controlled.

What Works Best Where

Quite clearly, any lighting system must first of all be dictated by practical considerations like the function of each room, since the aim should be to make each space as comfortable, easy to use, and safe as possible. Methods of lighting for cooking, washing, shaving, eating, writing, and reading all need a different approach, although rooms such as kitchens and bathrooms and passage ways and halls have fairly static lighting requirements. Living rooms in particular need to be extremely flexible, since in just one general area there will probably be a need for reading lights, perhaps a desk lamp and a light over a dining table, lights to illuminate pictures and objects, and general diffuse lighting.

Once plans have been made for each room and the furnishings decided, work out whether the space will be used more by night than by day; what type of lighting is needed (direct, indirect, concealed, background, very bright); whether any more electrical outlets, switches, or dimmers are needed and if so, where (for example, if an outlet would be useful in the middle of a floor, could it be done?). And think what style of lights would be best for each area. If spots or downlights are to be inset into a ceiling or at any great height, make sure that the bulbs will last a reasonable length of time and are easy to change and that the fixtures can be cleaned easily.

When the principles have been settled, it will be a great deal easier to make a final choice.

The Comfort Factor

Comfort in anything is always variable, and perhaps the best that can be said in lighting context is that light should never be uncomfortable. Of course, one can get used to poor lighting — one can get used to anything — but ideally it should not be a strain to carry out any visual task or occupation. Glare should be reduced to a minimum, which means that reflected light, which gives the least glare, should be used as much as possible for general illumination. And in order to avoid glare, lighting fixtures, when lit up, should not be very much brighter than their backgrounds. Nor should a light source be too close to the object that must be seen, because the brightness of the light will raise the adaption capacity of the eyes to a point at which the less bright object will be more difficult to see. This sounds complicated, but it makes sense.

A painting, for example, should not be hung next to a bright window unless there is some additional booster light available, either from another window at right angles or from artificial light. In fact, the position of all pictures should be chosen carefully and quite as much from the lighting viewpoint as from the aesthetic, especially when the pictures have glass fronts that pick up reflections.

Light and shade should be balanced. An evenly lit room can be boring at night and often curiously depressing, whereas areas of strong light where it is needed and dark shadow where it is not can be dramatic and interesting and still be comfortable. The whole point of good contemporary lighting is to have pools of light, with spots of accent light wherever they are useful.

The Safety Factor

There are enormous numbers of accidents in the home and thousands of death each year as a result of falls, particularly in the winter when it is darker. When assessing a home for potential accident areas, walk around it at dusk with the house or apartment unlit, remembering that eyes deteriorate with age so tht the average sixty-year-old needs twice as much light as the average thirty-year-old, and that what seems tolerably safe to a healthy adult might not be so for the elderly or for a small child- who might also be afraid of the dark. If these factors are borne in mind, possible accident areas should soon show themselves.

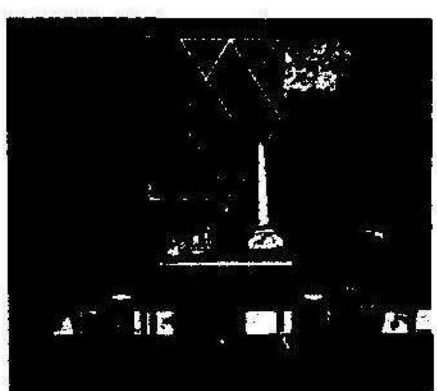
Stairs and corridors should be well lit at all times with light on the floor to show changes in levels or surfaces, and light on the walls to show switches and door handles. When starting the lighting plan from scratch, the ideal would be either to have a night circuit of low-level lights in these areas, controlled by a dimmer switch that can turn them down to right level at bedtime, or to have a separate circuit of miniature lights that could be left on the full twenty-four hours if desired because they consume a minimum of electricity. Although the latter is more expensive to install, it is convenient. Both types should provide a deterrent to burglars and prowlers.

There are also far too many accidents caused by a disregard of common-sense safety rules: by the failure to replace old and faulty wiring; by loading too few outlets with too many appliances; by the careless use of appliances near water; or by the thoughtless placement of cords leading from wall outlets to table or floor lamps.

To be safe as well as good, a lighting system should be neat, adequate for all present needs, and flexible enough to provide for unknown requirements in the future.

Uplights set close into a corner will define the parameters of a room. The same uplights set underneath glass shelves or side tables will add considerable sparkle, and if they are placed behind plants they will cast intricate shadows on the wall as well as glossing up the leaves.

Be careful about the angles of light sources like spots and downlights. Textures can be completely flattened by bad positioning of light sources, beautifully brought out by good. For example, a textured wall covering is accentuated by a ceiling-mounted downlight positioned close to the wall, but deadened by a spot trained full upon it.

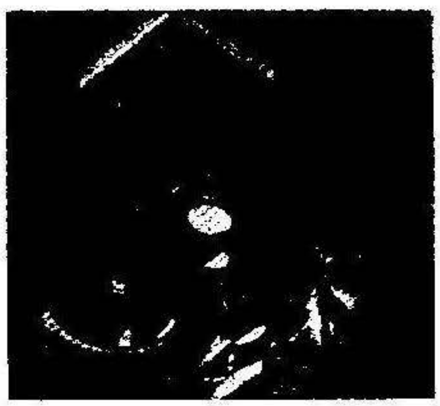


The lighter and whiter the surfaces in a room, the more they reflect the light. A dark-walled room will look surprisingly light with a white or off-white carpet and ceiling. And a general diffusing globe pendant hung in an all-white space will give a higher level of light than the same fixture in a darker-walled room.

During daylight hours, most windows will direct the light coming in onto the floor, which, if it is pale, will reflect the light upward. When a floor is dark, it will reflect less light and the room will naturally seen darker.

At night, the scene will change because light sources are inside the room. If their position is well chosen, they will give direct eight to ceiling and walls. Direct downlight on its own and shining on a dark carpet will be dramatic, certainly, but not bright enough for any sort of work.

The color of bulbs will change the feeling of room colors. For example, white bulbs cast a yellowish light but pink ones give a pleasantly mellow effect. And plain white walls can be refurbished practically at will by putting different-colored bulbs in two or three sockets, or by using colored filters over downlight, spot, or wallwasher fixtures.



Then too, quite different colors are reflected from different surfaces. When people are choosing clothes and fabrics in a store, they are likely to take them to a source of natural light to judge their "true colors," but they should take equal care to examine them in an artificial light as like as possible to the sort of night light that they use. Two fabrics that seem identical in color by day can look quite different at night, and even more peculiar under fluorescent tubes. Most reds, for instance, are emphasized by artificial light, while blues and greens tend to be diminished.

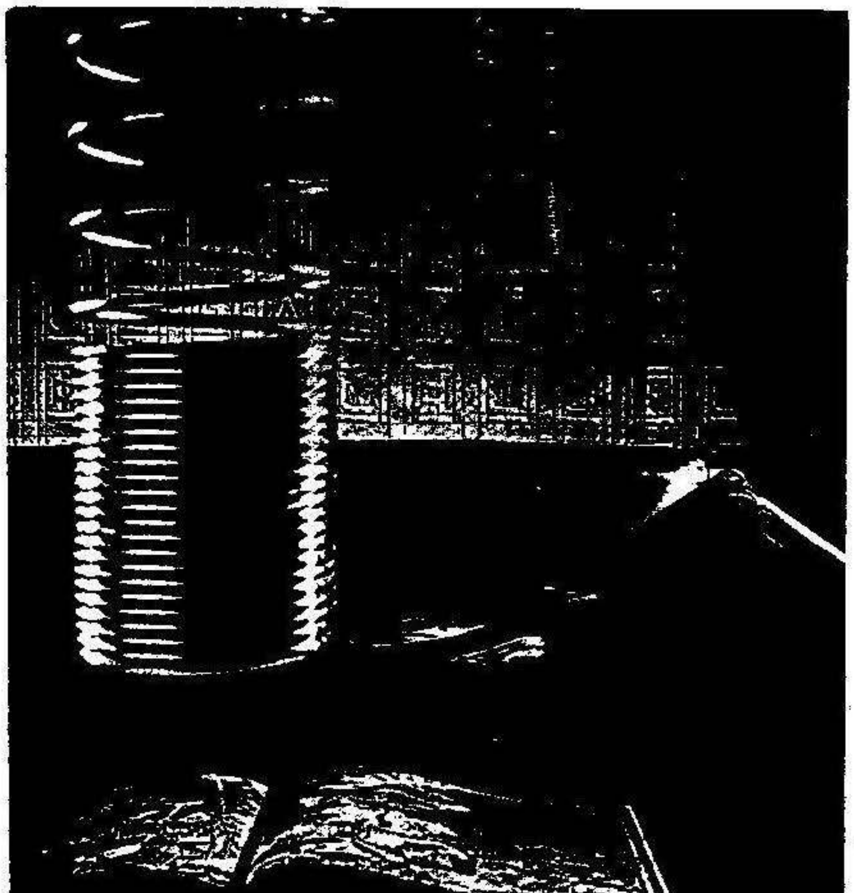
Lighting Different Areas

The following summary of the information given so far, plus tried and tested methods, might be helpful, even if it seems repetitive. Look back over the illustrations for other examples of the points raised.

Living Rooms

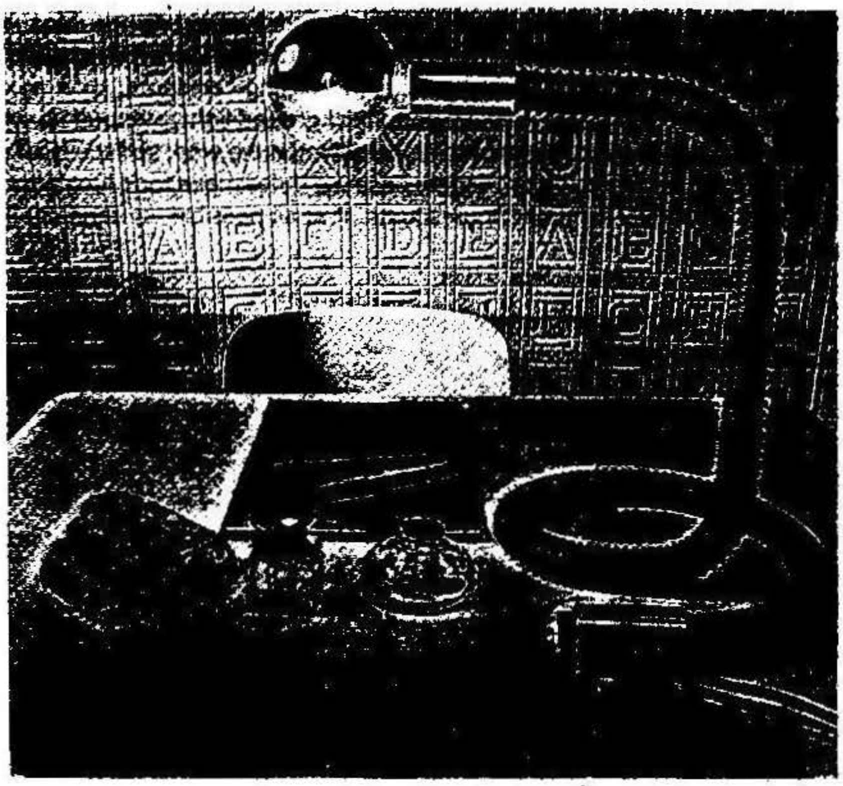
Sitting, talking, entertaining, listening to music, reading, writing, and watching television are the normal accepted activities in most living rooms, and therefore the best kind of light is a good measure of general or diffuse light with a play of light and shade. There should be adequate working light where necessary, and well-controlled highlighting for the more interesting display of art, plants, objects, and arrangements.

Most lighting designers agree that the best sort of general light is the reflected variety — light that bounces off a wall — because it gives the lest glare. This is obtained either from indirect sources like more or less concealed uplights, or from light concealed behind coves, or from wallwashers of one kind or another or from direct lighting like table and floor lamps.



Whatever happens, do not let general light be all at one level of brightness. Our eye see by means of contrasts, and nothing makes a room so flat, even boring, as bland light. Dimmers are a great help here with their easy-going control of intensity. And dramatic light can be provided by a mixture of judiciously placed downlights, and uplights, with highlights from spots.

Reading lights should be at a reasonable distance behind anyone reading, or if the light is a downlight, about a foot in front of the book or work; otherwise, the light on the page will be too bright. For writing, light should fall over the left shoulder of a right handed person and vice versa. Alternatively, a portable desk lamp or adjustable wall-mounted light should throw light onto the work.



Looking at television in an otherwise dark room is a strain. As a light near the viewer will reflect in the screen, a dimmed light behind the set is best if the set is on a shelf. If the set is free-standing, use a downlight or a floor lamp shining at the wall or down to the floor.

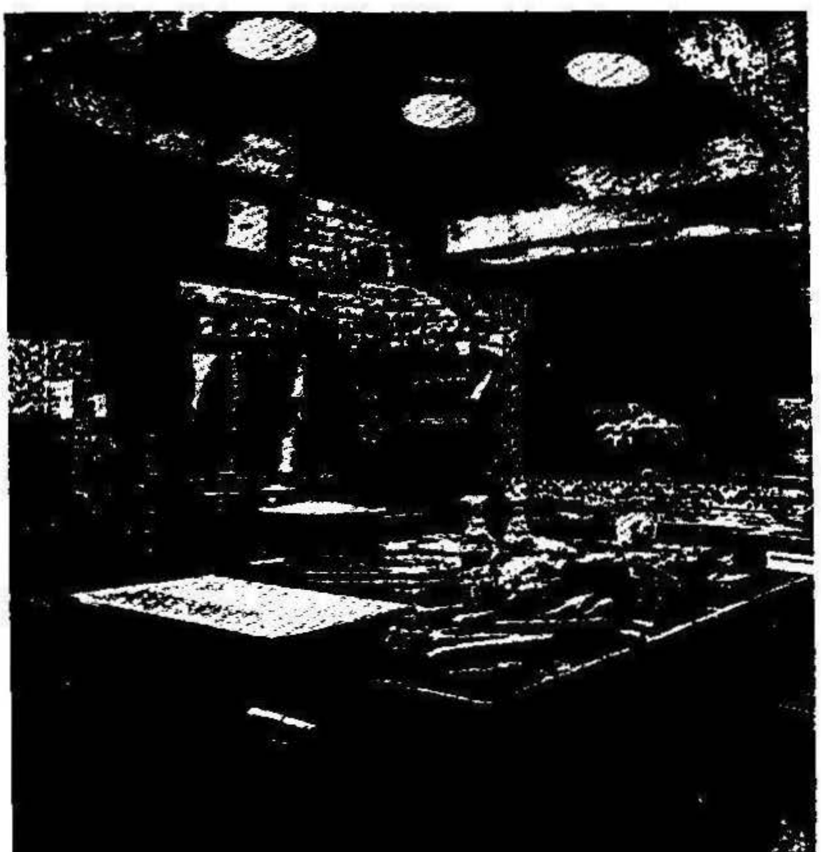
Dramatic lighting can be provided in storage units and on shelves or in alcoves. Collections of glass and ceramics look their best in front of a translucent wall of light (made by fixing vertical strip lights to the wall behind the shelves and concealing them with panels of pearly plexiglass, acrylic, or glass), or with a spot shining down on them from an angle. Single precious objects like a piece of sculpture, or even a plant or arrangement of flowers, are best

served by a single downlight set above them, and other shelves can be lit up the sides by baffled vertical strips. Objects on shelves can be picked out with tiny portable spots, and deeply recessed sections of wall units can be similarly treated.

Conventionally, paintings are lit from above by so-calleo picture lights, but they are better lit by spots fixed to the ceiling or walls, and better still by specific spots for the purpose, such as the parabolic variety with inbuilt transformers, or framming spots which can be specially adjusted to the size of the picture. These particular spots also make a dramatic job of lighting foliage, plants, or objects. An entire wall of paintings can be beautifully lit by plug-mold or a wash of light from recessed strips. This has the advantage of staying beautiful however much the paintings are juggled about.

Kitchen

A kitchen should have good general light plus booster light for any precise activity like studying cookbooks, chopping, assembling ingredients, and washing dishes. Most kitchens have a ceiling light-often a strip of fluorescence — and little else, but this can be harsh. Well-placed general diffusing lights fixed flush to the ceiling, or spots, or a mixture of wall-washers, downlights, and spots, make a good background light, stepped up with strip lights concealed under high-level cupboards to shine down on the work surface. Fluorescent lights should be the "de luxe warm white" variety because these make food look appetizing, which is more than one can say for most fluorescents. If at all possible, storage cupboards should be lit inside as well.



Halls, Corridors, and Staircase

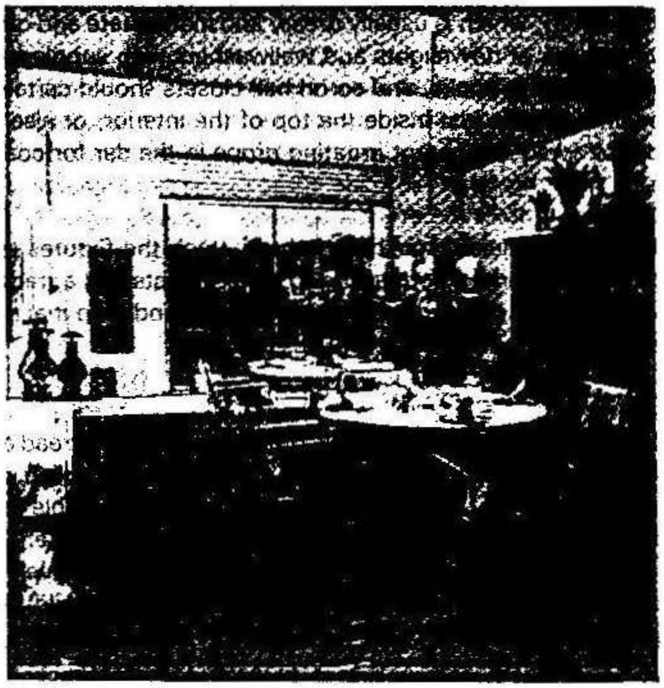
So many halls have only one ceiling outlet, which is usually dreary and inadequate and quite often unsafe. The ideal is to have a series of downlights and wallwashers with supplementary lighting for mirror, telephone, telephone books, and so on hall closets should certainly have an incandescent strip set behind a baffle just inside the top of the interior, or else an angled light on the ceiling outside, to avoid a constant irritating grope in the dar for coats.

If it is not possible to conceal the wiring required for these lights, attach the fixtures to a track, which, as I have explained, can be worked from a single outlet. If installing a track is difficult for one reason or another, run more cord from the original outlet and loop it across to another area, suspending the cord and extra light from a ceiling hook.

When stairs are properly lighted, there is a distinctly noticeable difference between tread and riser. The best way to achieve this is to have a strong light above the stairs and a softer one below. If the light are on a dimmer switch, they can be turned down to an acceptable level and left on all night with very little waste of power. This is especially useful in households where there are small children or elderly people. Alternatively, but more expensively, a separate night circuit of miniature lights can be installed. A cheaper solution would be a single low-wattage bulb in a well-chosen position.

Dining Areas

Candlelight has still not been bettered for dining, but make sure that the candles are either above or below eye level, not flickering directly in the dinerss eyes. Candlelight combined with a discreet downlight in the ceiling above the center of a round table, or at either end of a rectangular table, especially if the secondary lights are on a dimmer, is better still. Pendant lights with opaque shades cast a pleasant light downward, but they should be on rise-and-fall fixture and so placed that they do not throw light into people's eyes. The serving area should be lit separately, perhaps by a spot or wallwasher, or by concealed strip lighting above.



Bedrooms

Bedroom lighting usually needs to be as flexible as that in the living room: soft enough to be relaxing; bright enough to see to dress by; good enough at the dressing table for putting on makeup; well placed enough for comfortable reading in bed. Bedside-table lamps should be high enough to shine on a book, but not so high as to disturb anyone else. Small wall-mounted, adjustable spots or angled lamps are another good idea. Dimmers should provide all the variation needed for the main lighting.

Light above a mirror used for putting on makeup is not a good idea because it casts shadows under the nose and eyes. Lights side-positioned to shine outward rather than on the mirror itself are better. The same applies to long mirrors: the light should be directed on the viewer rather than on the glass.

Children's Rooms

All outlets should be childproofed, at least in small children's rooms, and lighting fixtures should be kept well out of reach. A dimmer is useful for children who are afraid of the dark; alternatives are one low-wattage bulb or the separate night circuit of miniature lights discussed earlier. Do not forget that older children will want to read in bed and probably to do homework in their rooms, so provide adequate reading lights in good positions.

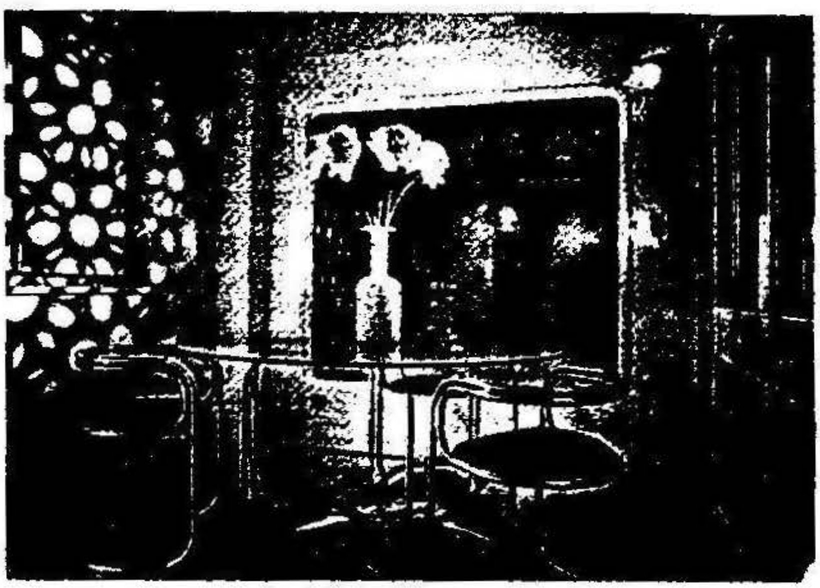
Bathrooms

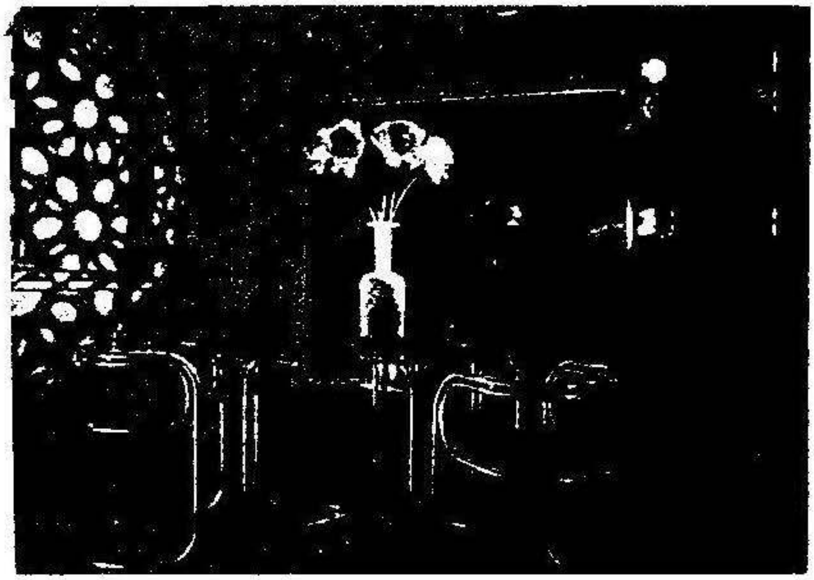
Small rooms may well only need one ceiling light and lights on either side of the mirror if it is to be used for shaving and putting on makeup, or just above it if only for shaving. It is irritating to have a baffled light over a mirror only to see the lighting fixture reflected in the mirror behind. Prevent this by inserting a smaller baffle between the bulb and the glass. Downlights are effective in bathrooms, too, and one over the bath is worth considering.

Furnishing with Light

Up to now, general lighting and its possibilities were discussed without going into the use of light as an integral part of the architecture and furnishing of a room. The more elaborate methods of defining spaces were not touched; the creation of whole walls of light, or the ways of making seating or tablets or seating platforms appear to float. Then there are the complete sound/light/air systems giving light, air conditioning, and hi-fi from the same series to tracks, and the sort of moving patterns and images that can be achieved in endless variable effects by lighting projectors, or spotlights shining through rotating wheels of colored lenses. It can all cost a lot of money, but there again, lighting like this is an art form in itself, and a particularly exciting one.

Light walls might seem light years away for most people, and yet they are comparatively easy to install instead of windows with depressing views or as a backing for a series of shelves or a background for display. To disguise a dreary view on an ugly window, install strip lighting or spots on the old wall and conceal the fixtures about a foot behind sheets of translucent white or off-white plexiglass fitted into a wood frame or frames that can slide on runners attached to ceiling and floor or remain static. Standard panels of plexiglass come in widths of up to 4 feet (122 centimeters), but they can be specially ordered in any size. Alternatively, it is possible to install panels of refractive glass between two rooms, or a room and a corridor, which will diffuse both daylight and artificial light in due season.





Paths and ribbons of light made from the plug-mold strips described on page 60, or simple strip lighting sunk into a recess and again covered with a translucent plexiglass or acrylic, can edge their way around the bottom of seating platforms or the top of conversation pits to particular effect. Cleverly placed tubes of neon can be amusing, especially in the context of a painted wall.

Other fascinating effects can be made by shining spots through any chosen object to cast intriguing shadows on the wall, especially when the spots shine through rotating the wheels of colored lenses mentioned above.

INSULATING AND SOUND-PROOFING

HOW MUCH INSULATION DO YOU NEED?

Key questions about insulation are how much do you need and how much can you afford? One way to answer them is by figuring out the "payback period," which is how long it takes to get your money back in lower energy bills. With fuel costs still rising, you might think that any money spent on insulation will be repaid quickly. Not true, installing insulation is sometimes an expensive affair, so it's important to put your money where it will do the most good in the shortest time.

The tables shown opposite will help you pinpoint the best investments for your particular use. If you follow this explanation and work through the accompanying examples, you'll be able to find the answers to those key questions about insulating your home.

The upper table gives individual energy index numbers (energy numbers) for eight different uses of insulation and two uses of storm windows and doors in homes in 20 cities. Under the name of the city is the type of heating and cooling system common in that area (New York City has two listings, for example).

The lower table works with the upper table to give you "energy payback numbers"—the energy numbers you'll need to repay an investment in seven years.

The numbers also include the assumption that energy costs will go up 10 percent each year and that money you use from savings to buy insulation will cost 6 percent in lost interest.

When using the tables, keep this formula in mind: If the pay back number in the lower table is less than the energy number in the top table, the payback period will be less than seven years. If the payback number is large than the energy number, the payback period will be more than seven years.

PLAYING OUR NUMBERS

Now let's look at a couple of examples. Assume you live in cleveland. You use gas heat and air conditioning and have some insulation in the house. Note that the energy number in the upper table for ceilings/attics in Cleveland is 2630. Now look at the lower table. The second category in the first column applies because you have less you decide to add R-19 insulation and do the work yourself. In that case, the payback number is 1610, which is a little more than half Cleveland's energy number of 2630. That means you should easily recope your investment in less than seven years.

Let's take another example. This time assume an oil-heated, air-conditioned home in New York. The front door is solid with no glass. Would it pay to install a storm door?

Look at the first table. The energy number for storm doors in New York is 3290. The lower table shows that adding a storm door to a single exterior door without glass has a payback number of 5380 if you do the work yourself. That new storm door will take nearly 11 years to pay for itself. Now, compute your own home's energy numbers. Find the City nearest your hometown. If you're in the middle between two cities, pick the one with climate most like your own. The formula provides a handy way to determine the value of your investment.

INSULATION PAYOFF INDEX

OH-Oil heat GH-Gas heat DE-Direct electric AC-Air conditioning

ENERGY INDEX APPLICABLE TO:	New York	New York	Wash., D.C.	Cleveland	Chicago	Atlanta	Miami	Memphis	New Orleans	Minneapolis	Kansas City	Dallas	Denver	Phoenix	Seattle	San Francisco	Los Angeles	Boston	Salt Lake City	Omaha	Albuquerque
	GH & AC	OH & AC	GH & AC	GH & AC	GH & AC	GH & AC	DE & AC	DE & AC	GH & AC	GH	GH & AC	GH & AC	GH	GH & AC	OH	GH	GH & AC	OH & AC	GH & AC	GH & AC	GH & AC
Ceilings/ attics	4490	4670	3410	2630	3170	2200	2410	2160	1850	3300	1920	2070	1610	2170	3480	1160	710	4500	1980	2240	2240
Ducts in attics	5410	5600	4020	2980	3760	2870	3870	2770	2720		2390	2850	1830	3210			670	4880	2350	2560	2680
Exterior frame walls (wood, brick siding)	4260	4440	3260	2550	3020	2040	2050	2010	1630		1800	1880	1550	1910			670	4410	1880	2160	2120
Storm windows or triple glass	3800	3980	2950	2380	2730	1710	1320	1700	1200		1570	1490	1440	1400			600	4230	1700	2010	1900
Storm doors*	3100	3290	2490	2120	2290	1210	230	1250	540		1220	910	1280	620			480	3970	1420	1770	1570
Floors over vented crawl spaces*	3100	3290	2490	2120	2290	1210	230	1250	540		1220	910	1280	620			480	3970	1420	1770	1570
Walls of unvented crawl spaces*	3100	3290	2490	2120	2290	1210	≤230	1250	540		1220	910	1280	620			480	3970	1420	1770	1570
Ducts in vented crawl spaces	4260	4440	3260	2550	3020	2040	2050	2010	1630		1800	1880	1550	1910			670	4410	1880	2160	2120
Walls of basements*	3100	3290	2490	2120	2290	1210	230	1250	540		1220	910	1280	620			480	3970	1420	1770	1570
Ducts in basement	5410	5600	4020	2980	3760	2870	3870	2770	2720	3300	2390	2850	1830	3210	3480	1160	670	4880	2350	2560	2680

*Energy index is for heating season only—air conditioning effect is negligible.

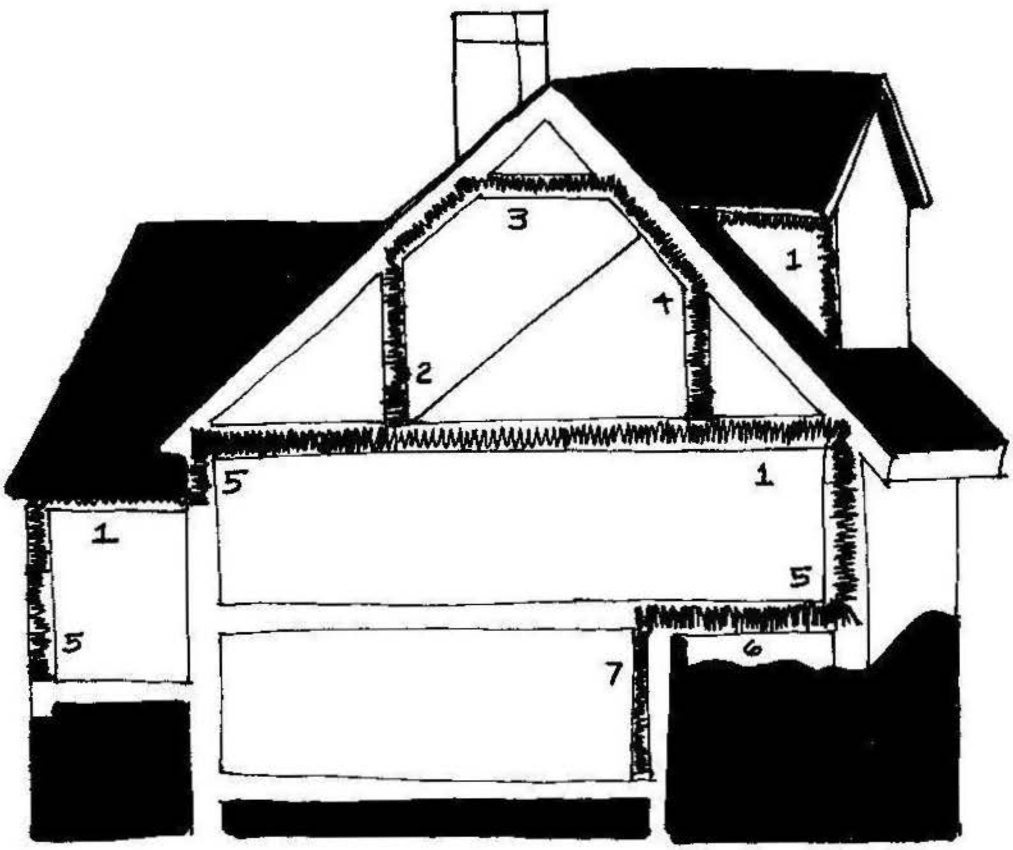
For a payback in seven years, I will need an energy index number of at least:

If I have:	And I want to:	If I do it myself	If I contract the work
No existing ceiling insulation	Add R-19 ceiling insulation	310	500
	Add R-30 ceiling insulation	390	630
Less than 3" of existing ceiling insulation	Add R-11 insulation	1340	2150
	Add R-19 ceiling insulation	1610	2580
	Add R-30 ceiling insulation	2120	3400
1" attic duct insulation	Add additional 1" duct insulation	1210	2420
More than 1" duct insulation	Add additional 1" duct insulation	2240	4480
Uninsulated exterior walls	Fill cavity with blown or foamed insulation	No	2960
Single exterior windows	Add storm windows	1930	2890
Double (insulating glass) windows	Add storm windows	3520	5270
Single exterior doors with glass	Add storm doors	3750	5360
Single exterior doors without glass	Add storm doors	5380	8070
Floors over vented crawl spaces with no floor insulation	Add R-11 floor insulation	830	1330
	Add R-19 floor insulation	2220	3560
Unvented crawl spaces—no wall or floor insulation	Add R-11 wall insulation	1740	2790
	Add R-19 wall insulation	4510	7220
Uninsulated ducts in vented crawl spaces	Add 1" duct insulation	3030	6050
	Add 2" duct insulation	3580	7160
Bare basement walls two feet or more above exterior grade	Add R-3 wall insulation	1730	2590
	Add R-11 wall insulation	3860	5780
Uninsulated ducts in basements	Add 1" duct insulation	2200	4400
	Add 2" duct insulation	2580	5160

If you add insulation to your home, the money you save will depend on the climate, the level of insulation already in your home and the cost of energy studies show the upgrading an older house that has inadequate insulation can reduce energy consumption by 50 percent, upgrading a newer, partially insulated home may mean saving of 20 to 30 percent.

KNOW WHAT YOU HAVE

Before rushing out to buy insulation, find out how much you already have. The illustrations below shows those areas in your home most likely to need extra insulation.



Places where you may need insulation are

1) Ceilings and unfinished attic floors, including dormer ceiling
2) Knee walls in a finished attic
3) Between attic collar beams
4) Sloping sections of a roof in a finished attic
5) Exterior walls
6) Floors above cold crawl spaces, over a porch or unheated garage
7) The outside walls of heated basements.

The easiest place to begin your survey is the attic. Use a ruler to measure the depth of the insulation in an unfinished attic. It maybe stapled to rafters or laid between floor joist, take care not to compact it.

Inspecting walls is a bit tougher. Remove the switch plate from an outlet, and peak into the wall cavity with a flashlight or make a small hole and patch it if you see any insulation your house is probably in pretty good shape if it is not, insulating a finished wall is best left to a professional (see topic on insulating walls).

In any event don't poke with sharp objects you may puncture a vapor barrier made from kraft paper, foil, or polyethylene, vapor barriers stop moisture from seeping into the insulation.

If you have vapor barriers, they should be facing heated areas—directly under floors, walls, and ceiling coverings.

INSULATING AND SOUND-PROOFING

Insulating your home will mean lower energy bills and better living. If both are comforting thoughts into action. Start at the top in your attic. Because warm air rises, uninsulated or poorly insulated attics allow valuable energy to slip away quickly, more quickly than any other spot in the house. If you button up your attic first, things will begin to improve immediately.

All attics aren't created equal. The way you insulate yours will depend on whether it is finished.

UNFINISHED ATTICS

In an unfinished attic that you do not intend to use as living space, place insulation in the floor (for add to it) to prevent losing beat from the rooms below. It spots such as this, use batts, blankets, or loose-fill insulation. Batts, made of fiber glass or rock wool, usually come with vapor barriers attached. Spread loose-insulation between joists, but add a vapor barrier first.

If you're working in an unfinished attic that has no floor, take some precautions. Install temporary lighting so you can see what you're doing, and place boards across the floors joists to use as a walkway.

FINISHED ATTICS

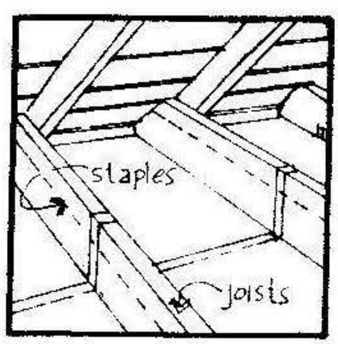
In a finished attic or in one you plan to finish, use blankets, batts, or loose-fill insulation.

If the attic ceiling is open, add rigid insulation, which consists of boards made from extruded polystyrene, urethane, or fiber glass. Nail the boards to the undersides of the exposed roof deck, using large-head, galvanized nails. (Roofing nails work well.) Nail on 8-inch centers in both directions, penetrating the wood at least 1¼ inches. Take care not to puncture the roof.

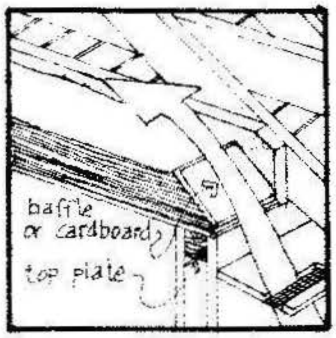
Because much rigid insulation is combustible, be sure to cover it with gypsum board before you put up paneling or other materials.

STEPS TO A SNUG ATTIC

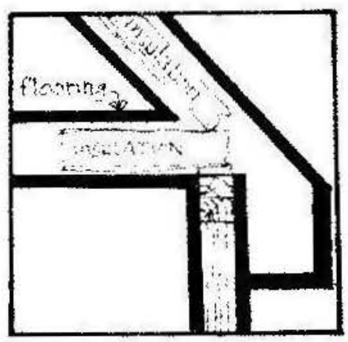
Add a vapor barrier when pouring loose-fill insulation or when installing unfaced batts or blankets on the attic floor. Use 2-mil polyethylene, smoothing it in place between and over the floor joists. Staple with care, and mend any tears in the barrier should always face the living area).



Adequate ventilation is important. Don't block eave vents when you install insulation. Extend it far enough to cover the top plate, but stop batts or blankets short of the vents. If you pour loose-fill insulation, install baffles.



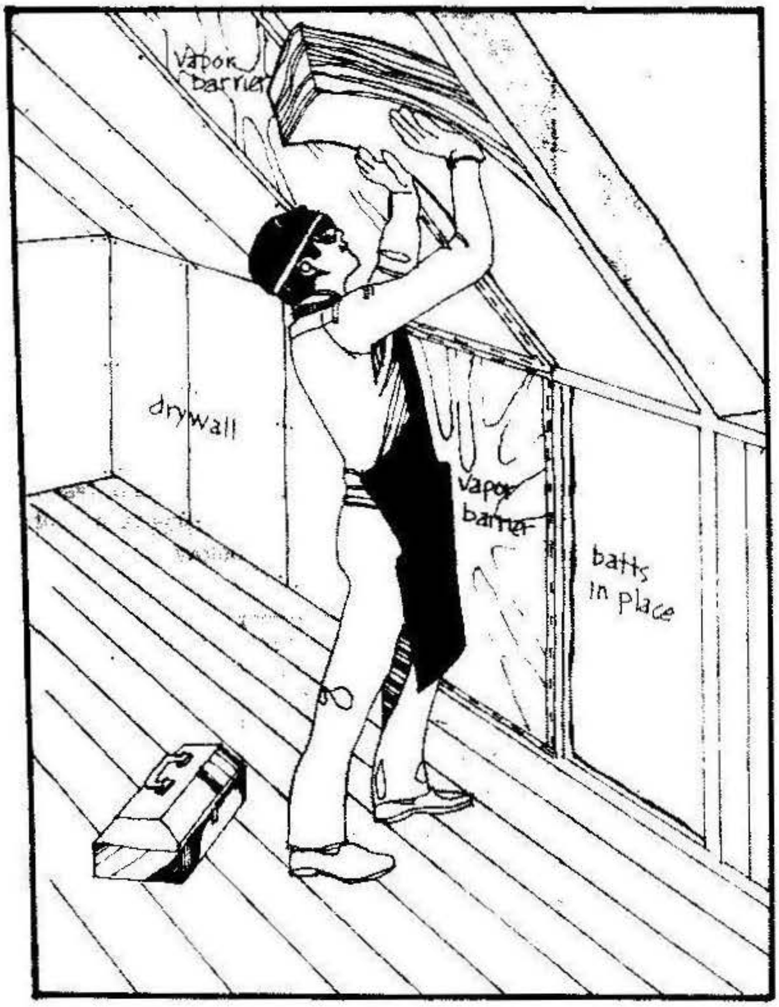
When adding insulation to both walls and floors, try to crate a continuous barrier so heat doesn't seep out at the eaves. Use a long stick to push batts into position. Cover the top plate with insulation, and keep it under wiring wherever possible.



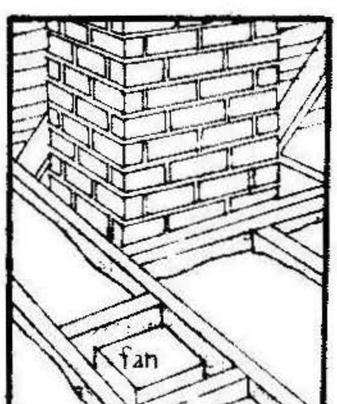
If you install blankets in the attic floor, unroll the insulation and cut it to the desired length. Press the blankets between the floor joists, then staple them to the inside of the joists, spacing staples every 6 to 8 inches.

To install blankets so they insulate a finished attic, start at the top plate of the knee wall. Cut the blankets and fit them between the wall studs. Make sure the vapor barrier is facing you, then staple the blankets into place. Don't try to run a continuous piece of insulation up one wall, across the collar beam, and down the other side, instead, use three separate pieces,

over-lapping the vapor barriers. If you use batts of unfaced insulation in a finished attic, cut them longer than required and wedge them into the stud space. Add a vapor barrier of polyethelene film.



Keep insulation away from recessed light fixture and exhaust fans. Covering them may create a fire hazard, instead, build baffles to keep the insulation at least 3 inches away from any motors or fixtures.



If you use loose-fill insulation in an attic floor, pour it between the joists to the desired depth. (Line the floor first with a vapor barrier.) Level the insulation with a wood slat or a rake as you work.

If your attic floor already has some insulation, use unfaced batts or blankets (those with no vapor barriers attached.) But if the floor is uninsulated, install faced batts or blankets. Be sure the vapor barriers point toward the heated areas below.

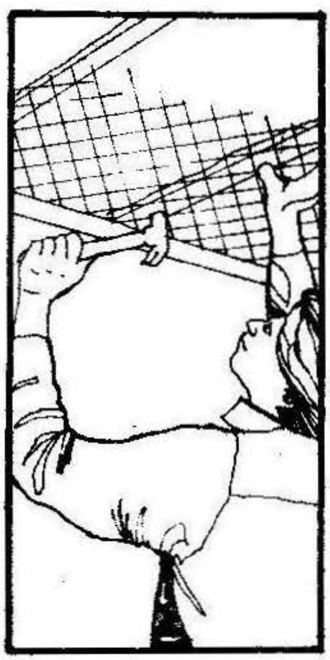
INSULATING FLOORS

After you insulate the attic, lower your sights and examine another energy-waster at floor level: your home's crawl space or basement. Once these areas are properly insulated, you'll warm up considerably. You can do both jobs yourself; they usually don't require the services of a professional.

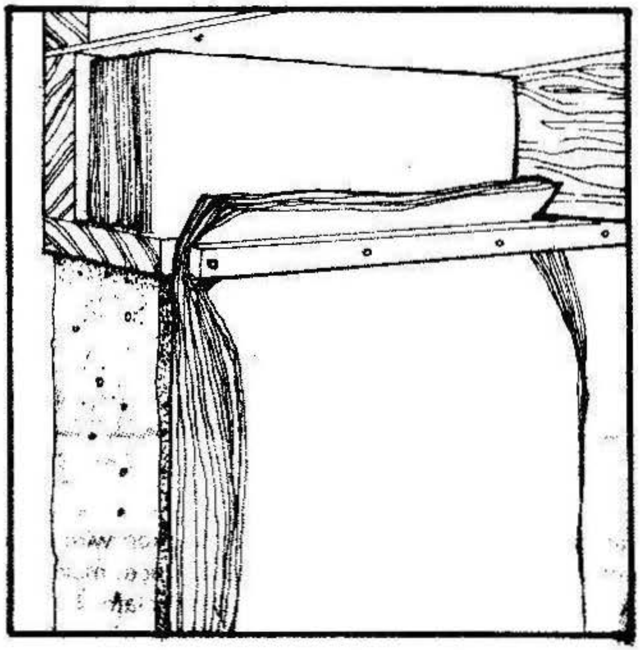
BUNDLING UP UNHEATED SPACES

1. Insulate the floors over unheated areas by working from below—in the basement, crawl space, or garage. You'll need batts or blankets of insulation, a tape measure, a heavy-duty staple gun and staples, wire mesh or chicken wire, shears to cut the wire, and a knife to cut the insulation. Staple the chicken wire or mesh to the bottom of the floor joists, then slide in blankets of insulation, working with small sections, vapor barrier up. Or you can use the method shown at left. Wedge batts or blankets into the space between floor joists. The insulation will temporarily stay in place without support.

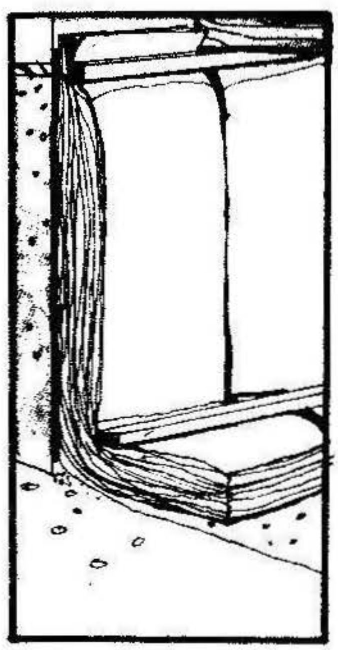
2. Beginning at one end, tack the wire mesh or chicken wire across the floor joists, as shown at left. Staple or nail one roll at a time in place, making sure the insulation fits snugly up to the band joist and overlaps the bottom plate. To do the same job. You can cover exposed joists with rigid urethane, polystyrene, or fiber-glass boards. Apply them with adhesive to the joists. Check the local building code to find out whether you need to cover the insulation with a fire-resistant material such as gypsum board, if the joists are covered, as they are in a finished garage ceiling. You best bet is to blow in loose-fill insulation.



3. For the walls in a crawl space, use batts or blankets. You'll need a sharp knife, tape measure, hammer, nails, furring strips or nailers, and gloves. Where joists run at right angles to the wall, tuck in small sections of insulation against the header. Cut longer pieces and attach them to the sill with furring strips, as shown at left. Extend insulation down the wall and 2 feet along the ground. Where joists run parallel to the wall, use longer pieces of insulation and nail them directly to the band joist.



4. After you install the insulation, lay a vapor barrier of 6-mil polyethylene on the ground, tucking it under the batts to the foundation wall. Tape the joints of the vapor barrier or lap them at least 6 inches. Finally, secure the polyethylene and insulation with rocks or 2 x 4 studs, as illustrated at left.



INSULATING WALLS

If you're up against a wall that needs insulation, don't despair. It's possible to blow or to spray insulating materials into finished exterior walls without ripping up those on the interior.

However, doing so is difficult and expensive. In all likelihood, you'll need the services of a contractor who has special equipment and experience to do the job properly. (Partly for these reasons, if your walls already have some insulation, it might might not be economical to add to it).

If you decide to go ahead, search carefully for a reputable professional. Try to get a number of written bids specifying R-Values, the amount of insulation required, and the overall cost of the job, in a properly insulated, standard 2 x 4 wall. You can reasonably expect R-8 for fiber glass or rock wool. R-10 for cellulose (both are blown in; see information at right), and R-11.5 for foam.

(One note of Caution: Don't use urea formaldehyde foam when insulating any area of the house. Recent studies suggest that the formaldehyde has given off by the insulation can cause health problems. In fact, the sale of urea formaldehyde foam has been banned by the U.S. Consumer Product Safety Commission. If you want the advantage of foam's higher R-Value, use another kind, such as urethane.)

Don't let insulating basement walls get you down, installing boards of rigid insulation and fitting in soft batts or blankets are two useful methods. The one to use depends partly on where you live and partly on how much room you're willing to take up with the installation.

THREE ALTERNATIVES

To install insulation in a finished wall, a contractor must reach all the spaces between studs in the wall cavity. For each space, the contractor removes the siding (he doesn't have to strip the entire wall) and drills holes, usually in the sheathing of the outside wall, as shown at left. Don't worry about all the drilling. A good contractor will leave no traces when the job is completed.

If the home has a brick-veneer exterior, the same procedure is followed except that it may be less expensive to do it from the inside of the wall.

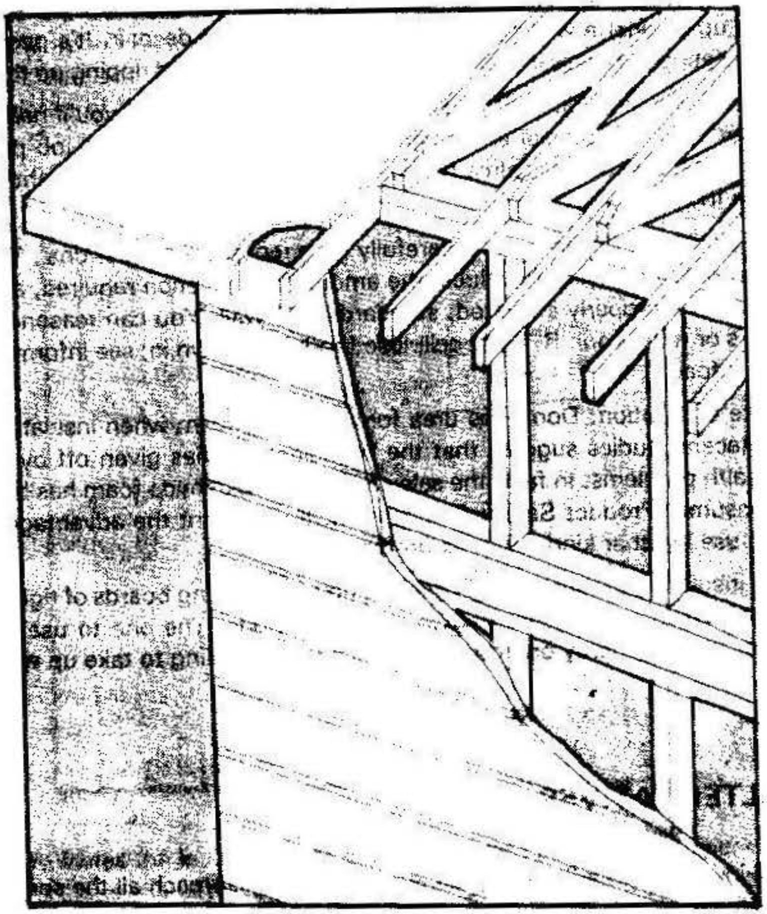
(Blowing insulation into a vertical space more than 4 feet high requires what is called the double-blow method. In this case, the contractor cuts two access holes for each stud.)

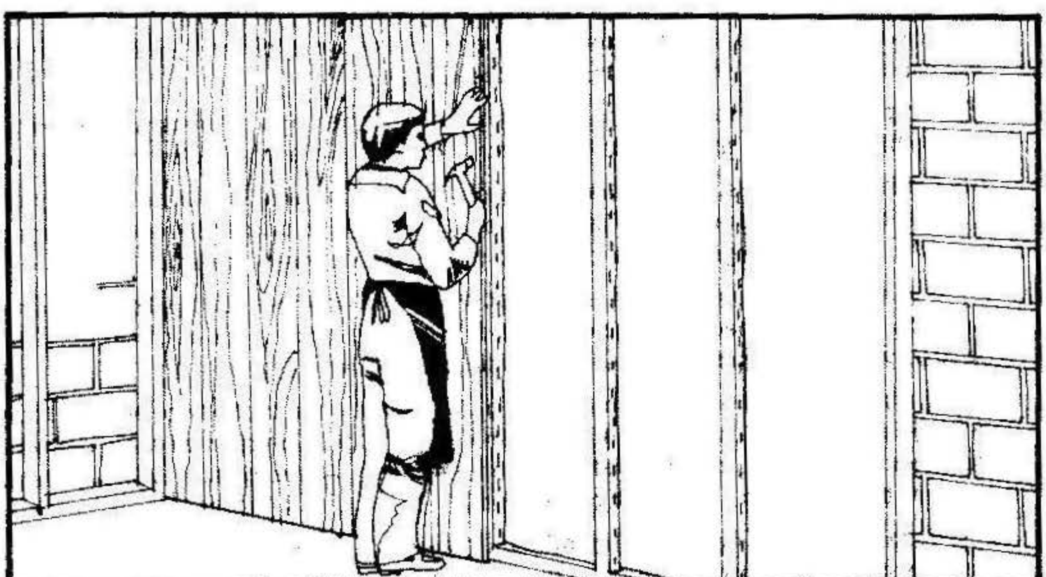
After drilling the holes, the contractor checks the spaces with a plumb bod, looking for obstructions below the hole. Then special equipments blows the insulation under air pressure through a large, flexible hose into the spaces between the studs.

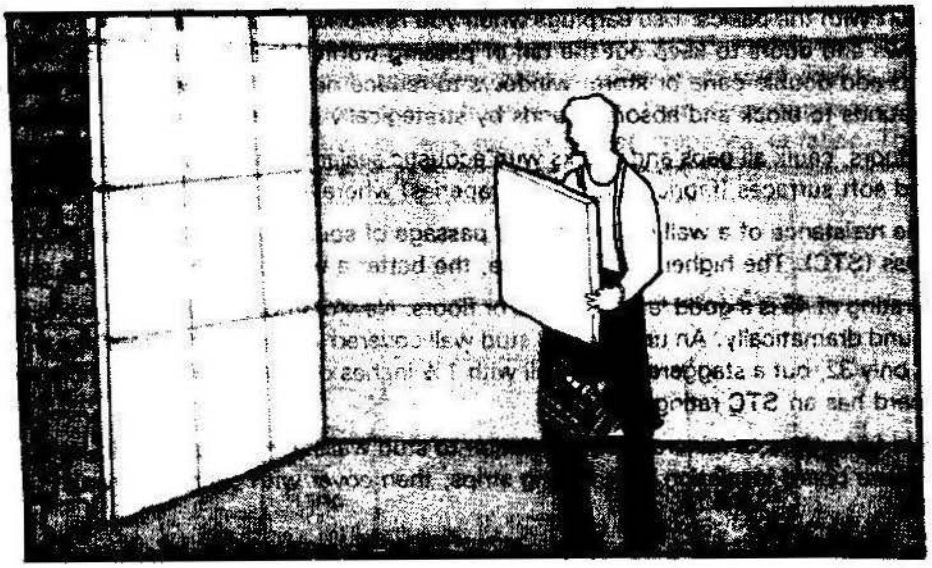
If the contractor is using foam, it is pumped through a hose with an applicator. With both methods, each wall space is completely filled. When the insulation is in place, the holes are covered with a rectainer or plug and the siding is replaced.

Frame a stud wall in the basement by nailing the bottom plate to the floor and the top plate to the joists. Nail in studs 18 or 24 inches on center. Tuck in batts or blankets between the studs, vapor barrier facing you, and staple them securely. Apply gypsum wallboard or paneling over the insulation, as shown on next page.

If you don't want to frame in a stud, use rigid boards to insulate basement walls. With masonry nails, attach furring strips to the walls and around windows and doors. Cut the insulation to fit, and apply it directly to the wall with mastic. Then cover the insulation with at least ½-inch-thick drywall.







In regions with mid winters, a rating of R-7 is sufficient. In colder areas, you'll need a minimum of R-11.

To reach either value using batts or blankets, you first have to frame out 2 x 3 or 2 x 4 stud walls over the top of the masonry. Then staple the soft insulating material, vapor barrier facing your, between the studs of the new buff-out walls. Don't be stingy with the staples; drive one every 10 or 12 inches. To finish, cover the studs with drywall or paneling.

Using rigid-board insulation allows the new wall to be as thin as possible, thereby saving a space in your basement. Line the walls with furring (to attach the finished wall material), then glue up or tuck in boards between it. (Rigid insulation often comes with an adhesive already applied.)

Because much, rigid insulation is combustible, cover it with a minimum of ½-inch drywall, even if you plan to install wood or hardboard paneling later.

Before starting either project, dry up your basement if it is wet. Moist insulation has no value at all. However don't be concerned by mind condensation. The insulation and vapor barrier usually will solve that problem.

Insulation becomes less important below ground level. Although insulating walls to their full height will provide benefits, you might decide to save money by insulating only down to ground level).

SOUNDPROOFING A ROOM

Common household noise can be irritating. Power tools, dryers, diswashers, kitchen blenders, and others noise-makers disturb the peace in nearly every American home. Putting your ear under a pillow or plugging your ears isn't the answer. Your can't eliminate all the noise from your life, but you can reduce its impact. By combining common sense with commonly available materials, you can sound-condition or even soundproof your rooms.

Although your home may not be as noisy as a factory, the jarring effect of household sounds can put you in a bad temper or give you a headache. Those reasons alone are enough to make you want to out a damper on the noise in home.

Start with the basics. Use earplugs when you're working with noisy power tools. Shut windows and doors to keep out the din of passing traffic. Apply weather stripping if needed, and add double-pane or storm windows to reduce noise from the outside. Landscape the grounds to block and absorb sounds by strategically locating trees, berms, and shrubs.

Indoors, caulk all gaps and cracks with acoustic sealant. Use solid-core doors, acoustic tile, and soft surfaces (fabric, carpeting, draperies) wherever noise is problem.

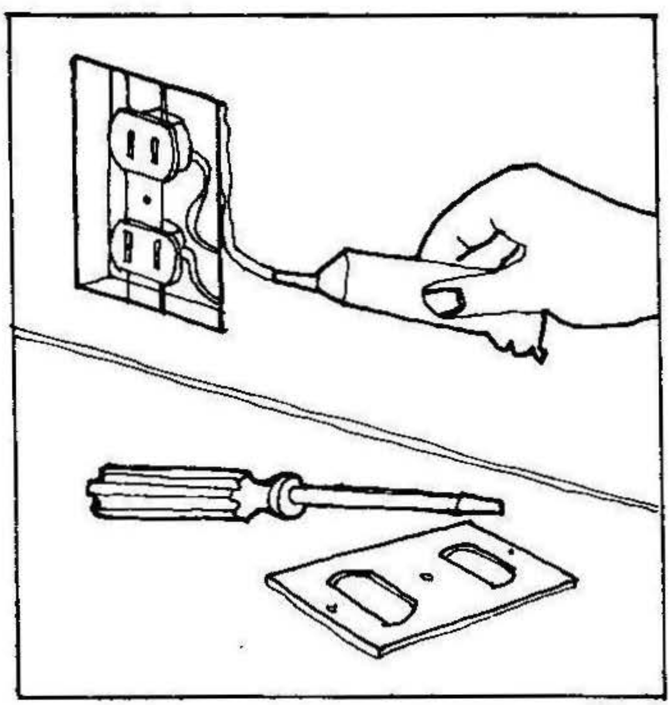
The resistance of a wall or floor to the passage of sound is rated by its sound transmission class (STC). The higher the STC value, the better a wall or floor blocks out sound.

A rating of 45 is a good level for walls or floors. New or improved insulation can help control sound dramatically. An uninsulated stud wall covered with gypsum board has an STC rating of only 32, but a staggered stud wall with 1 ½ inches of insulation and ½-inch gypsum wallboard has an STC rating of 49.

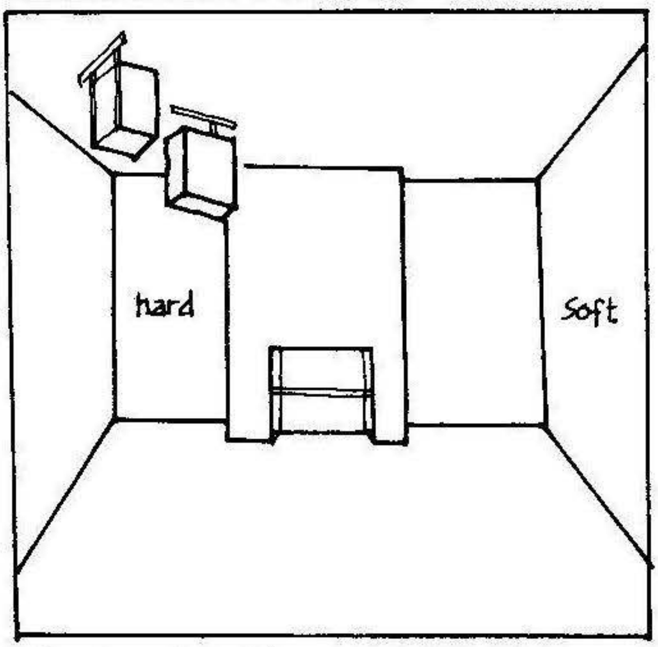
Add fiber-glass or mineral wool insulation to stud walls. On masonry walls, apply rigid polystyrene board insulation over furring strips, then cover with ½-inch drywall.

QUIET WALLS AND DOORS

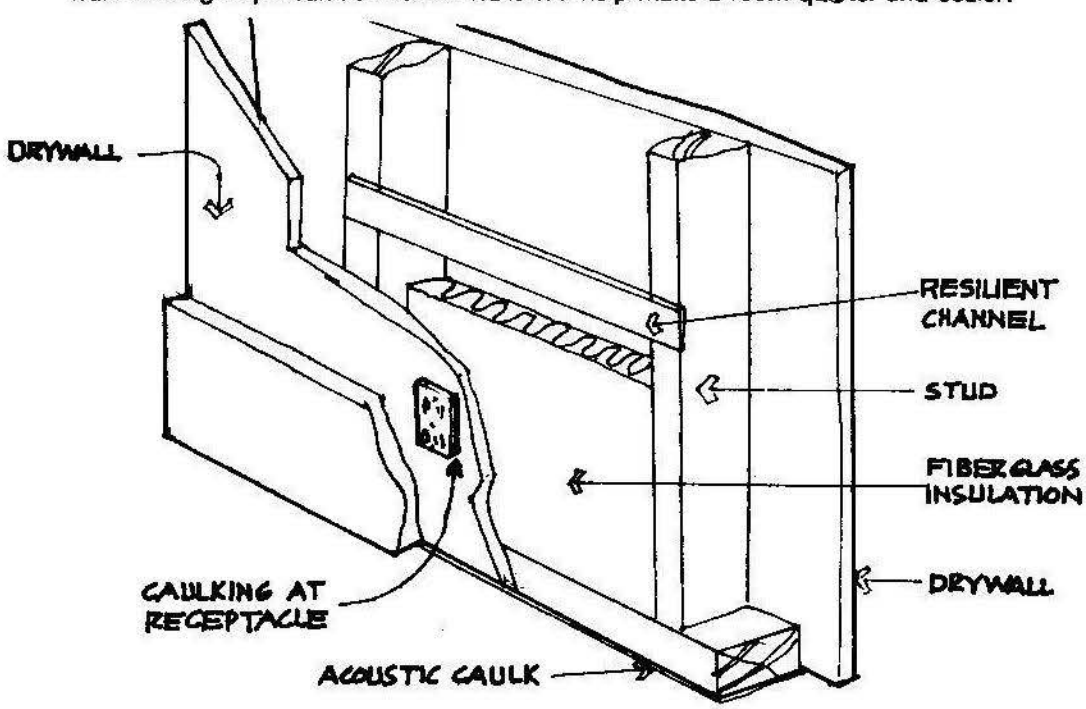
Start your attack on noise with the least expensive solutions, then move on to more costly steps if needed. First, pinpoint the source of noise and try to muffle it there, using carpeting, heavy draperies, and acoustic or cork tiles. Next, try caulking to block the transmission of sound from one from to another. If you're building a new wall, apply non-hardening acoustic caulk under the plates, at tops and bottoms of drywall panels, and around all receptacles, if you're trying to button up existing walls, remove the molding around the ceiling and baseboards and take off the outlet covers. Then apply an acoustic sealant as shown at left. Weather stripping windows also will help keep out noise.



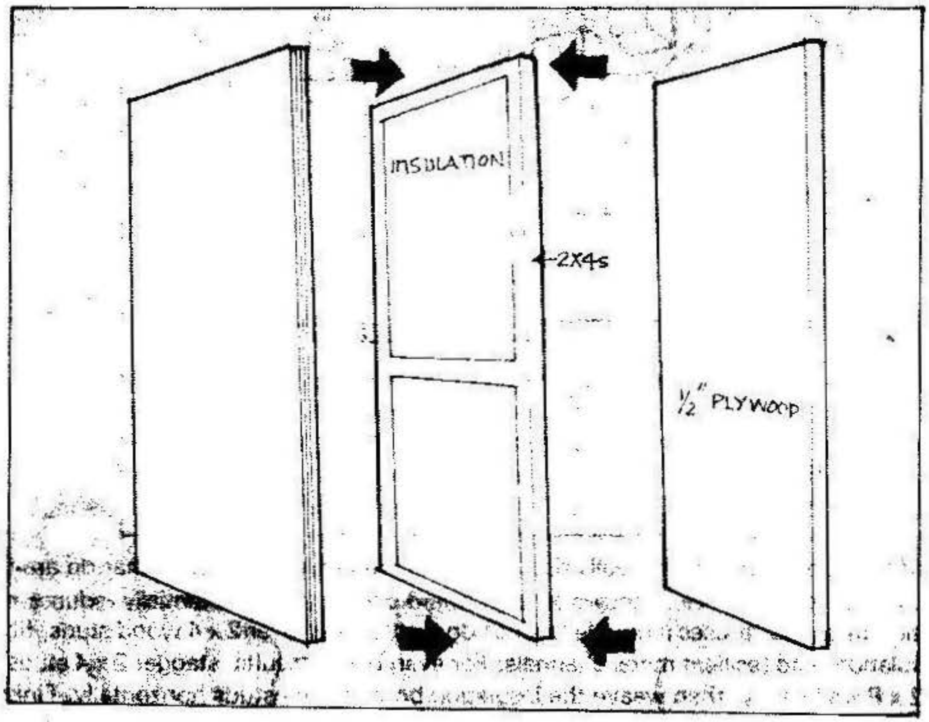
Effectively combining soft and hard materials is a simple way to control sound from loudspeakers. Fabric, carpets and drapes absorb sound well; wood, metal, and tile do not. Try the system shown below. Apply semigloss paint or adhesive-backed vinyl to plaster-board walls on the "hard" sides of the room to bounce sound. Then cover opposite walls and ceilings with soft, sound-absorbing materials such as carpet, draperies, or fabric. The music will sound better and will be less audible in adjoining areas.



Most wood-stud interior walls don't insulate sound well. The ones that do are built for the job. The drawing below shows an engineered system that substantially reduces the transmission of sound. It uses a double layer of drywall applied over 2 x 4 wood studs, fiber-glass insulation, and resilient metal channels. For even better results, stagger 2 x 4 studs to create a 2 x 6 wall cavity, then weave the insulation between the studs horizontally. Finish with drywall. Adding any insulation to the walls will help make a room quieter and cozier.



If you invest a few extra dollars in a solid-core door and add weather stripping around the door frame, you'll help keep sound from leaving the room. To make a quiet door, follow the drawings below. Cut four 8-foot 2 x 4s to fit the doorway, allowing ½ inch for new carpet or weather stripping. Next, assemble the 2 x 4s as shown, then glue and nail one sheet of 1½-inch plywood to the 2 x 4 frame. Stuff and staple insulation in place. Glue and nail the second sheet of plywood to the other side. Hinge the door so it opens into the room, then apply self-stick weather stripping.



GUIDELINES FOR ENERGY CONSERVING

DESIGN OF BUILDINGS AND UTILITY SYSTEMS

ection 1.0 PURPOSE

1 To encourage and promote the energy conserving design of buildings and their services to reduce the use of energy with due regard to the cost effectiveness, building function, and comfort, health, safety and productivity of the occupants.

2 To prescribe guidelines and minimum requirements for the energy conserving design of new buildings and provide methods for determining compliance with the same to make them always energy-efficient.

ection 2.0 APPLICATION AND EXEMPTION

1 Requirements are set forth for the design of new energy-efficient buildings for human occupancy, covering their exterior envelopes and the selection of their systems and equipment for power, lighting, air conditioning and other energy-consuming auxiliary systems.

2 These guidelines are applicable to the design of new buildings classified as offices, hotels, shopping centers and hospitals as well as those portions of industrial buildings that are used primarily for human occupancy.

3 Buildings with industrial and/or process requirements may exclude those areas devoted to the process from these requirements. Buildings or portions thereof whose peak design rate of energy usage is less than 10 W/m^2 of gross floor area for all purpose are excluded from these requirements.

ection 3.0 LIGHTING

.1 Scope

.1.1 Interior spaces of buildings;

.1.2 Exterior areas of buildings such as entrances, exits, loading docks, parking areas, etc.;

.1.3 Roads, grounds and other exterior areas including open-air covered areas where lighting is required and is energized through the building's electrical service.

.2 Exemptions

.2.1 Industrial areas of manufacturing concerns, storage areas and processing facilities.

.2.2 Areas devoted for theatrical productions, television broadcasting, audio-visual presentations and those portion of entertainment facilities such as stage areas in hotel ballrooms, discos, night clubs and casinos where lighting is an essential technical element.

2.3 Specialized luminaries for medical or dental purposes.

.2.4 Outdoor athletic facilities.

.2.5 Display lighting required for art exhibit or display in galleries, museums and monuments.

2.6 Exterior lighting for public monuments.

2.7 Special lighting for research laboratories.

2.8 Emergency lighting that is automatically "off" during normal operations.

2.9 High risk security areas identified by local ordinances or regulations or by security or safety personnel as requiring additional lighting.

2.10 Classrooms specifically designed for the hard-of-seeing, hard-of-hearing and for elderly persons.

2.11 Lighting for dwelling units.

3.3 General Requirements of Energy-efficient Lighting Design

3.3.1 The lighting system shall be chosen as to provide a flexible, effective and pleasing visual environment in accordance with the intended use, but with the least possible energy requirements. The use of task-oriented lighting shall be used whenever practicable. In the design of general lighting in buildings with centralized air conditioning equipment, consideration should be given to integrated lighting and air conditioning systems which use luminaries with heat removal capabilities.

3.3.2 The lighting system shall be designed for expected activity. The task shall be analyzed in terms of difficulty, duration, criticalness and location in order to determine the lighting needs throughout the space, always keeping in mind that higher illumination levels than necessary are likely to waste energy while on the other hand, levels lower than needed could impair visual effectiveness. Table 3.1 lists the recommended illuminance levels.

3.3.3 The most efficient lamps appropriate to the type of lighting, color rendition and color appearance shall be selected. The use of such types of lamps reduces power requirements. Table 3.2 shows that high intensity discharge lamps are more efficient than incandescent lamps.

Table 3.1 RECOMMENDED DESIGN ILLUMINANCE LEVELS

Task	Min. & Max. (Lux)	Applications
Lighting for infrequently used areas	50 - 150	Circulation areas and corridors
	100 - 200	Stairs, escalators
	100 - 200	Hotel bedrooms, lavatories
Lighting for working interiors	200 - 300	Infrequent reading and writing
	300 - 750	General offices, typing and computing
	300 - 750	Conference rooms
	500 - 1000	Deep-plan general offices
	500 - 1000	Drawing offices
Localized lighting for exacting tasks	500 - 1000	Proofreading
	750 - 1500	Designing, architecture and machine engineering
	1000 - 2000	Detailed and precise work

Table 3.2 EFFICACY RANGES AND COLOR RENDERING INDICES OF VARIOUS LAMPS

Lamp Type	Efficacy Range (*) (lumens/watt)	Color Rendering Index (CRI)
Incandescent Lamp (10-100 W)	15-25	100
Fluorescent Lamp (10-40 W)	50-95	52-86
HP Mercury Fluorescent (50-2000 W)	40-63	20-45
Metal Halide (up to 10000 W)	75-95	70
LP Sodium Lamp (20-200 W)	100-180	--
HP Sodium Lamp (50-100 W)	80-130	25

Note: (*) Values exclude power usage of ballasts.

3.3.4 In general, the normal artificial light source should be the fluorescent lamp. In downlight installation, high pressure discharge lamps can be used. In large high bay areas, high pressure discharge lamps should be used. Where good color rendering is required, the tubular fluorescent lamp and other high pressure sodium lamps should be used. However, if moderate color rendering is of comparatively minor importance, high pressure sodium lamps can be used. If very good color rendering is required, the tubular fluorescent lamp should be used.

3.3.5 The most efficient combination of luminairies, lamps and ballasts appropriate for the lighting task and for the environment shall be selected so that lamp light output is used effectively. The selected luminaire should meet the requirements with respect to light distribution, uniformity and glare control. The use of highly polished or minor reflectors is recommended to reduce the number of lamps installed without reducing the illumination level. Where ballasts are used, these should be of the low loss type and with a power factor of at least 85%.

3.3.6 The highest practical room surface reflectances should be considered in the lighting design. The use of light finishes will attain the best overall efficiency of the entire lighting system. Dark surfaces should be avoided because these absorb light. Table 3.3 lists the recommended room surface reflectances.

Table 3.3 RECOMMENDED ROOM SURFACE REFLECTANCES

Surface	% Reflectance
Ceilings	80 - 92
Walls	40 - 60
Furnitures	26 - 44
Floors	21 - 39

Table 3.4 MAXIMUM LIGHTING POWER DENSITY FOR BUILDING INTERIORS

Area/Activity	Lighting Power Density (W/m^2)
Auditoriums, Churches	8
Food Service	
Snack Bars and Cafeteria	14
Leisure/Dining Bar	10
Offices and Banks	21
Retails Stores (*)	
Type A (**)	23
Type B (***)	22
Shopping Centers/Malls/Arcades	15
Clubs/Basements/Warehouses/ General Storage Areas	2
Commercial Storage Areas/Halls Corridors/Closets	4
Schools	
Preparatory/Elementary	17
High School	18
Technical/Universities	18
Hospitals/Nursing Homes	16
Hotels/Motels	
Lodging rooms/Guest rooms	12
Public Areas	17
Banquet/Exhibit	20

Notes: (*) *Includes general merchandising and display lighting except for store front, etc.*
(**) *Type A - Fine and mass merchandising.*
(***) *Type B - General, food and miscellaneous merchandising.*

3.3.7 Selective switching possibilities should be provided : that individual or specific group of fixtures can be turne off when not needed and lighting levels can be adapte to changing needs.

3.3.8 The lighting system shall be so designed that daylightir can be coordinated with artificial lighting, taking in consideration the problems of glare, brightness imba ance and heat buildup in the building interior.

3.3.9 In selection lighting systems, the costs of operation ar energy usage and not simply the initial cost should t considered.

3.4 Maximum Allowable Power Density for Building Inte rior Lighting Systems

3.4.1 The total lighting load for the interior spaces of building shall not exceed the summation of the maximum value for building areas/activities as specified in Table 3.4.

3.5 Maximum Allowable Power Density for Building Exte rior Lighting Systems

3.5.1 Basic lighting power requirements for building exterio shall not exceed the values given in Table 3.5.

3.5.2 Basic power lighting requirements for roads ar grounds shall not exceed the values given in Table 3.6.

Table 3.5 MAXIMUM VALUES FOR LIGHTING POWER FOR BUILDIN EXTERIORS

Building Area/Space	Lighting Power
Exits (w/ or w/o canopy)	60 W/Lm of door opening
Entrance (w/o canopy)	90 W/Lm of door opening
Entrance (w/ canopy)	
High traffic (e.g., retail, hotel airport, theater, etc.)	100 W/m^2 of canopied area
Light traffic (e.g., hospital, office, school, etc.)	10 W/m^2 of canopied area
Loading area	3 W/m^2
Loading door	50 W/Lm of door opening
Total power allowance for the exterior (inclusive of above allowances) of building perimeter for buildings of up to 5 storeys (above ground) plus 6 W/Lm of building perimeter for each additional storey	100 W/Lm

Note: W/Lm = Watts per linear meter

Table 3.6 MAXIMUM VALUES FOR LIGHTING POWER FOR ROADS AN GROUNDS

Area/Space	Lighting Power (W/m^2)
Store and work area	2.0
Other activity areas for casual use (e.g., picnic grounds, gardens, parks, etc.)	1.0
Private driveways/walkways	1.0
Public driveways/walkways	1.5
Private parking lots	1.2
Public parking lots	1.8

3.6 Lighting Controls

All lighting systems except those required for emergency o exit lighting for security purposes shall be provided with man ual, automatic or programmable controls.

6.1 Each space enclosed by walls or ceiling-height partitions shall be provided with at least one lighting control, capable of turning off all the lights within the space.
Exception:
Continuous lighting required for security purposes.

6.2 One lighting control point shall be provided for each task location or group of task locations within an area of $45 m^2$ or less.

6.3 The general lighting of any enclosed area $10 m^2$ or larger in which the connected load exceeds $10 W/m^2$ for the whole area shall be controlled so that the load for the lights may be reduced by at least 50% while maintaining a reasonably uniform level of illuminance throughout the area. This may be done with the use of dimmers, by dual switching of alternate lamps, or by switching each luminaire or each lamp.

6.4 The minimum number of controls required shall be determined using Table 3.7 which lists the types of lighting controls and the equivalent number of control points they represent. The minimum number of controls, however, shall not be less than one for each 1500 W of connected lighting load.

6.5 Exterior lighting not intended for 24 hours continuous use shall be automatically switched by a timer, photocell or a timer-photocell combination but provided with manual override.

6.6 Hotel and motel guest rooms, except bathrooms, shall have one master switch at the main entry door that turns off all permanently wired lighting fixtures and switched receptacles, except for security lighting, if required. This switch may be activated by the insertion and removal of the room key.

ble 3.7 CONTROL TYPES AND EQUIVALENT NUMBER OF CONTROL POINTS

pe of Control	Equivalent Number of Control Points
anually operated on-off switch	1
ccupancy Sensor	2
mer - programmable from the space being controlled	2
Level step-control (including off) or pre-set dimming	2
Level step-control (including off) or pre-set dimming	3
ntinuous (Automatic) dimming	3

6.7 Where adequate daylighting is available, local manual or automatic controls such as photo-electric switches or automatic dimmers shall be provided in daylighted spaces. Controls shall be provided so as to operate rows of lights parallel to facade/exterior wall.

.8 Feature display lighting in retail and wholesale stores shall be separately switched on circuits not more than 20 amperes. If there are more than four of these display circuits, the display lighting shall be automatically controlled by a programmable timer with provisions for temporary override by store personnel.

.9 Valance lighting in retail and wholesale stores shall be switched independent of general and display lighting.

Control Location

.1 All lighting controls should be so located to be readily accessible by space occupants.

.2 Switches provided for task areas, if readily accessible, may be mounted as part of the task lighting fixtures. Switches controlling the same load from more than one location should not be credited as increasing the number of controls to meet the requirements of Section 3.6.
Exceptions:
1. Lighting control requirements for spaces which must be used as a whole should be controlled in accordance with the work activities and controls may be centralized in remote locations. These areas include public lobbies of office buildings, hotels and hospitals; retail and department stores and warehouses; storerooms and service corridors under centralized supervision.
2. Manual and automatic control devices may reduce the number of controls required by using an equivalent number of controls from Table 3.7.
3. Automatic controls.
4. Programmable controls.
5. Controls requiring trained operators.
6. Controls for safety hazards and security.

Section 4.0 ELECTRIC POWER AND DISTRIBUTION

4.1 Scope
This section applies to the energy conservation requirements of electric motors, transformers and distribution systems of buildings except those required for emergency purposes.

4.2 Electric Motors

42.1 This section shall apply to all permanently wired squirrel-cage induction type motors of 0.4 kW size and larger serving the building. It shall not apply to other types as regards efficiency requirements.

4.2.2 Motors expected to operate more than 500 hours a year shall have full load efficiencies not less than the values shown in Table 4.1.

4.2.3 The nameplates of these motors shall include not only all the information required by the Philippine Electrical Code, Part 1, but also the rated full load efficiency and full load power factor.

Table 4.1 MINIMUM ACCEPTABLE FULL LOAD EFFICIENCY

Motor Size	Min. Efficiency (%)
0.4 kW (1/2 HP)	77.0
0.8 kW (1 HP)	82.5
4.0 kW (5 HP)	84.0
8.0 kW (10 HP)	87.5
40.0 kW (50 HP)	89.5
80.0 kW (100 HP)	91.0
100.0 up (150 HP)	91.7

Notes: 1. Table 4.1 applies to single speed polyphase squirrel-cage induction motors with nominal speeds of 1200, 1800 or 3600 RPM at 60 Hz with open, drip-proof or totally enclosed fan-cooled enclosures.

2. Motors operating more than 750 hours per year should be of the high efficiency type with efficiencies higher than those listed. High-efficiency motors are presently available with typical nominal efficiencies of:

4.0 kW	*89.5 %*
8.0 kW	*91.0 %*
40.0 kW	*92.1 %*
75.0 kW	*95.1 %*
150.0 kW	*96.2 %*

3. Motors with ratings different from those listed shall have efficiency ratings higher or greater than those listed for the next lower size.

4.2.4 Motor Selection

4.2.4.1 The type and the size of the SC induction motor shall be selected only after an accurate determination of the starting and running requirements of the load has been made, taking into account the following factors:
1. maximum overload expected
2. ambient conditions
3. power supply conditions
4. future expansion
5. deterioration of the driven load
6. duty cycle
7. speed

4.2.4.2 The first five factors above should be considered carefully as they suggest the selection of larger motors at the expense of low power factor and low efficiency.

4.2.4.3 In cases where higher kW rating is necessary due to special requirements of the application, the motor rating may be increased but not to exceed 125% of the calculated maximum load to be served. If this rating is not available, the next higher rating may be selected.

4.2.4.4 Loads of lower duty cycle may be powered by smaller motors which will have good overall efficiencies.

4.2.4.5 Motors with high speeds are generally more efficient than those of lower speeds and should be considered as much as possible.

4.2.4.6 Where an application requires varying output operation of motor-driven equipment such as a centrifugal pump, a variable speed induction motor with a variable frequency supply should be considered instead of throttling the output of the pump. The former is a high efficiency operation, while the other is a low efficiency operation.

4.2.4.7 High efficiency motors are basically high flux density, low core loss and low current density motors which should be applied properly in order to obtain maximum energy savings.

4.2.4.8 Other applicable requirements specified in the Philippine Electrical Code, Part 1 shall be complied with.

4.3 Transformers

4.3.1 All owner-supplied transformers that are part of the building electrical system shall have efficiencies not lower than 90% at rated load conditions.

4.3.2 The average power factor of the loads being served by the transformers at any time should not be less than 85%. In cases where load power factors are below this value, capacitors or power factor improving devices shall be provided so that automatic or manual correction can be made.

4.3.3 Transformer load grouping schemes shall be so designed such that the transformers are loaded to not less than 75% of their full load ratings and that no-load circuits or partially loaded circuit combinations should be minimized as much as possible.

4.3.4 Disconnect switches or breakers shall be provided for transformers which are anticipated to have no loads during certain periods.

4.3.5 The transformers should be located inside a building so that water, dirt, heat and corrosive atmosphere will not impair the efficiency and operation of the transformers. However, sufficient ventilation should be provided.

4.3.6 Where it is necessary to install transformers within a building space which is air-conditioned, the space shall be enclosed by acceptable means and provided with appropriate temperature-control fan to exhaust generated heat to the outside.

4.3.7 The installation of transformers indoors shall comply with Article 6.9 -- "Transformer and Transformer Vaults" of the Philippine Electrical Code, Part 1.

4.3.8 In the selection of transformers, extreme care should be exercised so that they are not unjustifiably large. Oversized transformers operate at low power factor and low efficiency.

4.3.9 In order to minimize heat losses due to current, the transformers should be set such that the utilization voltage is on the higher end of the allowable voltage range so that motor currents, line currents and transformer currents are reduced. In this manner, the I^2R losses is reduced and efficiency is improved.

4.4 Power Distribution

4.4.1 All distribution lines that lead to the different loads and equipment, such as lights, motors and transformers, have resistances and therefore heat up. These affect the efficiency of distribution and therefore should be minimized.

4.4.2 In the calculation of the wire sizes to be used, the Philippine Electrical Code, Part 1 has specified the procedure and the factors to be considered in order to arrive at the minimum acceptable wire size.

4.4.3 To conserve energy, the wire size should be increased by one or two sizes depending on which is more critical: first cost or energy cost.

4.5 Sub-metering and Check-metering

4.5.1 Buildings whose designed connected electrical load is over 250 kVA shall have the distribution system designed to include sub-metering facilities.

4.5.2 The electrical power feeders for each facility of the building for which sub-metering is required shall be subdivided into the following categories:

4.5.2.1 Lighting and receptacle outlets;

4.5.2.2 Power systems (for ventilation and air-conditioning, elevators, computers, etc.).

4.5.3 In multiple tenant buildings, each tenant unit shall have a provision for measuring the tenant's energy consumption. Power to common utilities such as water pump, elevator, etc. need not meet these tenant sub-metering provisions.

4.5.4 The feeders for each category in Section 4.5.2 may include provisions for check metering for energy conservation monitoring.

4.5.5 In order to facilitate check-metering safely and quickly by qualified personnel, an adequate working space in front of the electrical panels and meters shall be provided.

Section 5.0 BUILDING ENVELOPE

5.1 Scope

This section applies to air-conditioned buildings with a total cooling load of 175 kW or greater. The requirements and guidelines of this section cover external walls (with and without daylighting), roofs (with and without skylights) and air leakage through the building envelope.

5.2 Exterior Walls (without Daylighting)

5.2.1 The design criterion for building envelope, known as the Overall Th mal Transfer Value (OTTV), shall be adopted. The OTTV requireme which shall apply only to air-conditioned buildings is aimed achieving the energy conserving design of building envelopes so as minimize external heat gain and thereby reduce the cooling load of t air-conditioning system.

5.2.2 The Overall Thermal Transfer Value (OTTV) for the exterior walls buildings shall not exceed 48 W/m². The OTTV for all walls of building is the weighted average of all OTTV's ($OTTV_i$) computed f the individual walls.

5.2.3 The Overall Thermal Transfer Value ($OTTV_i$) for each exterior wall se tion that has a different orientation shall be determined using Equati 5.1.

$$OTTV. = 12.65\ A\ (1\text{-}WWR)\ U_w + 3.35\ (WWR)\ U_g + SF\ (WWR)\ SC$$

[Equation 5.Ia - Offic

$$OTTV = 5.40\ A\ (1\text{-}WWR)\ U_w + 1.10\ (WWR)\ U_g + SF\ (WWR)\ SC$$

[Equation 5.Ib - Hote

where: A = Solar absorptance of the opaque wall. Typical valu are given in Table 5.1;

WWR = Window-to-wall ratio for the orientation under consid ation;

Uw = U-value of the opaque wall (W/m²-°C). Thermal condu tivities of building materials are given in Table 5.2;

Ug = U-value of window glass (W/m²-°C). Typical U-values glass are given in Table 5.5;

SF = Solar Factor (W/m²). The SF values for the different c entations are listed in Table 5.6;

SC = Shading coefficient of window glass. Values of SC a given in Table 5.7. Manufacturers data may also be used.

5.2.4 The Overall Thermal Transfer Value (OTTV) for the total wall area of building shall be determined using Equation 5.2. The OTTV is weighed average of the $OTTV_i$'s for each wall calculated using Equ tion 5.1.

$$OTTV = \frac{A_1\ (OTTV_1) + A_2\ (OTTV_2) + \ldots + A_i\ (OTTV_i)}{A_1 + A_2 + \ldots + A_i}$$

[Equation 5

where: A_i = Gross area of the ith exterior wall (m²). The gro area includes the opaque wall surface and the window surface the wall being considered.

$OTTV_i$ = Overall thermal transfer value for the ith wall, as c culated using Eqn. 5.1.

Table 5.1 PERCENTAGE OF SOLAR RADIATION ABSORBED BY S LECTED BUILDING MATERIALS

Building Material	Percentage ('
Brick (common)	
Light red	55
Red	68
Marble	
White	44
Dark	66
Polished	50-60
Metals	
Steel	45-81
Galvanized iron, new	64
Galvanized iron, dirty	92
Copper, polished	18
Copper, tarnished	64
Lead sheet, old	79
Zinc, polished	46
Paints	
White emulsion	12-20
White paint, 4.3 mm on aluminum	20
White enamel on iron	25-45
Aluminum oil base paint	45
Gray paint	75
Red oil base paint	74
Black gloss paint	90
Green oil base paint	50
Black paint, 4.3 mm on aluminum	94-98
Roofing materials	
Asbestos cement, white	42
Asbestos cement, 6 mos. exposure	61
Asbestos cement, 12 mos. exposure	71

Asbestos cement, 6 yrs. exposure	83
Asbestos cement, red	69
Tile clay, red	64
Tile	65-91
scellaneous	
Aluminum, polished	15
Concrete	60
Concrete, rough	60
Plaster, white wall	7
Wood	60
Asbestos cement board, white	59
Aluminum foil	15
ound cover	
Asphalt pavement	93
Grass, green after rain	67
Grass, high and dry	67-69
Sand, dry	82
Sand, wet	91
Sand, white powdered	45
Water	94
Vegetable fields and shrubs, wilted	70
Common vegetable fields and shrubs	72-76
Ground, dry and plowed	75-80
Bare moist ground	90

here specific material is not mentioned above, an approximate value ma assigned with the use of the following color guide:

olor	% Absorption
hite, smooth surfaces	25 - 40
ray to dark gray, light green	40 - 50
reen to dark green, red, brown	50 - 70
ark brown, blue	70 - 80
ark blue, black	80 - 90
erfectly black	100

able 5.2 THERMAL CONDUCTIVITIES OF BUILDING MATERIALS

onstruction aterials	Density (kg/m3)	Thermal Conductivity (W/m-oC)
sbestos cement sheet	1488	0.317
sbestos insulating board	720	0.108
sphalt, roofing	2240	1.226
tumen		1.298
rick:		
(a) common	1925	0.721
(b) face	2085	1.297
oncrete	2400	1.442
	64	0.144
oncrete, light weight	960	0.303
	1120	0.346
	1280	0.476
ork board	144	0.042
ber board	264	0.052
ber glass (see Glass Wool and Mineral Wool)		
lass, sheet	2512	1.053
lass wool, mat or guilt (dry)	32	0.035
ypsum plaster board	880	0.170
ard board:		
(a) standard	1024	0.216
(b) medium	640	0.123
etals:		
(a) Aluminum alloy, typical	2672	211
(b) copper, commercial	8784	385
(c) steel	7840	47.6
ineral wool, left	32-104	0.032-0.035
aster:		
(a) gypsum	1216	0.370
(b) perlite	616	0.115
(c) sand/cement	1568	0.533
(d) vermiculite	640-960	0.202-0.303
olystyrene, expanded	16	0.035
olyurethane, foam	24	0.024
VC flooring	1360	0.713
oil, loosely packed	1200	0.375
tone, tile:		
(a) sand stone	2000	1.298
(b) granite	2640	2.297
(c) marble/terrazzi ceramic mosaic	2640	1.298
Tile, roof	1890	0.836
Timber:		
(a) across grain softwood	608	0.125
(b) hardwood	702	0.138
(c) plywood	528	0.138
Vermiculite, loose granules	80-112	0.065
Wood chipboard	800	0.144
Woodwool slab	400	0.086
	480	0.101

Note: Thermal conductivities are per unit of length thickness.

Table 5.3 AIR SPACE RESISTANCES FOR WALLS AND ROOFS

Type of Air Space	Thermal Resistance (m^2-^0C/W)		
	5 mm	20 mm	100 mm
Air Space Resistances (R_a) for Walls			
Vertical air space (Heat flows horizontally)			
(a) High Emissivity	0.110	0.148	0.160
(b) Low Emissivity	0.250	0.578	0.606
Air Space Resistances (R_a) for Roof			
Horizontal or sloping air space (Heat flows downward)			
(a) High Emissivity			
(i) horizontal air space	0.110	0.148	0.174
(ii) sloped air space 22.5°	0.110	0.148	0.165
(iii) sloped air space 45°	0.110	0.148	0.158
(b) Low Emissivity			
(i) horizontal air space	0.250	0.572	1.423
(ii) sloped air space 22.5°	0.250	0.571	1.095
(iii) sloped air space 45°	0.250	0.570	0.768
Attic Space Resistances (R_{attic})			
(a) High Emissivity		0.458	
(b) Low Emissivity		1.356	

Notes: 1. Ordinarily, high emissivity is assumed for air spaces bounded by building materials of moderately smooth surfaces. Low emissivity only applies where one or both sides of the air space is bounded by a reflective surface such as that of an aluminum foil.

2. Interpolation within the range of pitch angles from horizontal to 45° is permitted. For angle beyond 45°, the value for 45° can be used; no extrapolation is needed.

3. Interpolation with the range of thickness from 5 mm to 100 mm is permitted. For air space less than 5 mm, extrapolation basing on $R_a = 0$ for zero thickness is allowed; otherwise R_a is assumed to be zero. For air space greater than 100 mm, the R_a for 100 mm should be used, i.e. extrapolation is not permitted.

4. In the case of air space in roof, reflective foil used should be installed within the reflective surface facing downward as dust deposit will render an upward-facing surface ineffective after a while.

Table 5.4 SURFACE FILM RESISTANCES

Type of Surface	Thermal Resistance (m^2-^oC/W)
Walls	
Inside surface	
Smooth finishes	0.12
Reflective finishes	0.30
Outside surface	0.04
Roofs	
Inside surface	
Flat (smooth finish)	0.16
45° sloped (smooth finish)	0.15
Flat (reflective finish)	0.80
45° sloped (reflective finish)	0.39
Outside surface	
Flat or sloped	0.56

Note: Interpolation between angle of slope from horizontal to 45° is valid.

Table 5.5 GLASS THERMAL TRANSMITTANCE VALUES

Glass Type	U-Value (Glass only) (W/m^2-°C) Exposed	Sheltered
Flat Glass		
Single pane, clear	5.91	4.60
Single pane, with low emittance, coating		
e = 0.60	5.68	4.54
e = 0.40	5.11	3.97
e = 0.20	4.26	3.12
Insulating Glass		
Double pane, clear		
4.8 mm air space	3.69	3.29
6.4 mm air space	3.46	3.12
12.5 mm air space	3.18	2.95
Double pane, with low emittance coating		
e = 0.60	3.01	2.78
e = 0.40	2.67	2.44
e = 0.20	2.21	2.04

To account for outside or inside sashes/frames, the following correction factors shall be used:

Glass Type	Correction Factors Inside		Outside	
	Exposed	Sheltered	Exposed	Sheltered
Single pane				
Clear	0.48	0.60	0.48	0.60
Low e	0.50	0.56	0.65	0.77
Double pane				
Clear	0.64	0.65	0.65	0.66
Low e	0.71	0.70	0.80	0.98

Table 5.6 SOLAR FACTORS FOR VARIOUS BUILDING WALL ORIENTATIONS

Orientation	Type A (W/m^2)	Type B (W/m^2)	Type C (W/m^2)
North	88.2	101.0	96.7
East	184.3	202.4	166.2
South	138.9	165.1	157.2
West	154.5	175.7	182.2
Northeast	133.7	145.9	122.0
Southwest	150.1	174.6	176.8
Southeast	176.0	199.5	171.6
Northwest	119.1	134.3	138.8
Average (All Orientations)	143.1	162.3	151.4

Notes: *Type A - All daylight hours operation (e.g., Hotels, Hospitals).*
Type B - Operation between 0700 HRS to 1700 HRS (e.g., Offices).
Type C - Operation between 0900 HRS to 1800 HRS (e.g., Stores).

Table 5.7 GLASS SHADING COEFFICIENTS

Glazing Type	Shading Coefficient
Single Glass	
3 mm Clear	1.00
6 mm Clear	0.95
13 mm Clear	0.88
6 mm Heat Absorbing	0.67
13 mm Heat Absorbing	0.50
Reflective, coated	0.30-0.60
Insulating Glass	
6 mm air space 13 mm air space	0.89
Clear Out and In	0.83
Heat Absorbing Out and In	0.55
Reflective, coated	0.20-0.40

Notes: *1. For reflective glass, see manufacturer's literature for exact values.*
2. For shading coefficients of glass with indoor shading devices see Chapter 27 of ASHRAE Handbook of Fundamentals (1989).

5.3 Exterior Walls (with Daylighting)

5.3.1 The calculation procedure for the OTTV of exterior walls considering daylighting is the same as given in Section 5.2. The daylighting aspect is explained in the following sections.

5.3.2 A credit for daylighting is provided for several reasons. In daylighting applications, the window to wall ratio (WWR) is usually large. Glazing allows more heat gain to the interior space than an isolated wall and due to this, a larger WWR normally causes a higher level of cooling needs in the space. However, artificial lighting energy savings due to daylighting can be greater than the additional energy penalty for space cooling due to the increased glazed surface area when the building envelope is carefully designed to allow daylighting. The transparent portions of the building envelope should be designed to prevent solar gains above that necessary for effective daylighting. To make sure that daylighting is being effectively utilized, automatic daylighting controls shall be used to turn off the artificial lights when sufficient natural light is available.

5.3.3 Daylighting credit may be taken for those areas with installed automatic lighting controls for all lights within 4 meters of an exterior wall. Daylighting credit is accounted for by a 10% reduction in the $OTTV_i$'s (as calculated using Equation 5.1) of that particular wall where daylighting is applied. These reduced $OTTV_i$ values are then used in the calculation of the building's OTTV using Equation 5.2.

5.3.4 If the automatic daylight control credit is taken, then the visible transmittance of the fenestration system used for that exterior wall(s) where daylighting is applied shall not be less than 0.25.

5.4 Roofs (without Skylights)

5.4.1 Solar heat gain through the roof can contribute a substantial amount to the cooling load of an air-conditioned building. Hence, roofs should be provided with adequate insulation in order to conserve energy.

5.4.2 All roofs shall be provided with insulation. Roofs shall not have a thermal transmittance value greater than the values listed in Table 5.8.

Table 5.8 MAXIMUM THERMAL TRANSMITTANCE VALUES OF ROOFS

Weight Group	Weight Range (kgs/m^2)	Max. U-Value ($W/m2$-°C)
Light	Under 50	0.50
Medium	50-230	0.80
Heavy	Over 230	1.20

5.4.3 The use of reflective coatings which are reasonably impervious to moisture degradation are strongly recommended for roofs as top overlays.

5.4.4 The values in Table 5.8 may be exceeded by 50% if any one of the following applies:
1. The roof area is shaded from direct solar radiation by ventilated double roof;
2. External roof surface reflective treatments are used where the solar reflectivity is equal to or greater than 0.7 and the treatment is free from algae growth.

5.5 Air Leakage

5.5.1 General
The infiltration of warm air and exfiltration of cold air contribute substantially to the heat gain of an air-conditioned building. As a basic requirement, buildings must not have unenclosed doorways, entrances, etc., and where heavy traffic of people is anticipated, self-closing doors must be provided.

5.5.2 Windows
Windows shall be designed to limit air leakage. The air infiltration rate shall not exceed $2.8m^3/hr$ per linear meter of sash crack when tested under a pressure differential of 75 Pa. Manufacturers shall provide documentation certifying compliance with this criterion.

5.5.3 Swinging, Revolving or Sliding Doors
These types of doors shall be used at all entrances and they shall be designed to limit air leakage. The air infiltration rate shall not exceed $61.2\ m^3/hr$ per linear meter of door crack when tested under a pressure differential of 75 Pa. Manufacturers shall provide documentation certifying compliance with this criterion.
Air curtains may be used in very high volume entrances only when revolving or self-closing sliding doors are not appropriate.

5.5.4 Effective means of caulking and weatherstripping shall be used to seal all penetrations through the exterior surfaces of the building.

ction 6.0 AIR CONDITIONING SYSTEM

Scope

The requirements in this Section represent minimum design criteria. The designer should evaluate other energy conservation measures which may be applicable to the proposed building.

Load Calculations

.1 Calculation Procedures

Cooling system design loads for the purpose of sizing system and equipment should be determined in accordance with the procedures in the latest edition of the ASHRAE Handbook of Fundamentals or other equivalent publications.

.2 Indoor Design Conditions

The indoor conditions in an air-conditioned space shall conform to the following:

1. Design Dry Bulb Temperature	25°C
2. Design Relative Humidity	55%
3. Maximum Dry Bulb Temperature	27°C
4. Minimum Dry Bulb Temperature	23°C
5. Maximum Relative Humidity	60%
6. Minimum Relative Humidity	50%

te: Indoor design conditions may differ from those presented above because of special occupancy or process requirements, source control, air contamination or local regulations.

.3 Outdoor Design Conditions

The outdoor conditions shall be taken as follows:

1. Design Dry Bulb Temperature	34°C
2. Design Wet Bulb Temperature	27°C

.4 Ventilation

The quality and quantity of air used to ventilate air-conditioned spaces shall always be sufficient and acceptable to human occupants and comply with applicable health and/or air quality requirements. Ventilation requirements shall conform to the following design criteria (Table 6.1).

Exception:

Outdoor air quantities may exceed those shown in Table 6.1 because of special occupancy or process requirements, source control, air contamination or local regulations.

ble 6.1 OUTDOOR AIR REQUIREMENTS FOR VENTILATION

cility/Area	Outdoor Air Requirements (l/s) Smoking	Non-Smoking
mmercial Stores		
Sales floors & showrooms	12.5	2.5
Stockrooms	12.5	2.5
Dressing rooms	12.5	2.5
Malls & arcades	5.0	3.5
Shipping & receiving areas	5.0	2.5
Warehouses	5.0	2.5
Elevators	-	7.5
Smoking areas	25.0	-
orts & Amusement Facilities		
Ballrooms & discos	17.5	3.5
Bowling alleys (seats)	17.5	3.5
Gymnasiums	-	10.0
Spectator areas	17.5	3.5
Game rooms	17.5	3.5
tels & Other Lodging Facilities		
Bedrooms (S/D)	15.0 (b)	7.5 (b)
Living rooms (suite)	10.0 (b)	5.0 (b)
Baths, toilets	25.0 (b)	25.0 (b)
Lobbies	7.5	2.5
Conference rooms (small)	17.5	3.5
Large assembly rooms	17.5	3.5
fices		
Work areas	10.0	2.5
Meeting & waiting areas	17.5	3.5
spitals		
Patient rooms	17.5 (c)	3.5 (c)
Medical procedure areas	17.5	3.5
Operating rooms	-	10.0
Recovery & ICU rooms	-	7.5
Autopsy rooms	-	30.0
Physical therapy areas	-	7.5
ucational Facilities		
Classrooms	12.5	2.5
Laboratories	-	5.0
Training shops	17.5	3.5
Libraries	-	2.5
Auditoriums	-	3.5

otes: *(a) All figures are in liters per second (l/s) per person, except:*
(b) Unit is on a per room basis;
(c) Unit is on a per bed basis.

6.3 System Design and Sizing

Air conditioning system and equipment shall be sized as close as possible to the space and system loads calculated in accordance with Section 6.2. The design of the system and the associated equipment and controls should take into account important factors such as nature of application, type of building construction, indoor and outdoor conditions, internal load patterns, control methods for efficient energy utilization and economic factors.

6.3.1 Engineered systems and equipment should be properly sized and selected to meet maximum loads and should have good unloading characteristics to meet the minimum load efficiently. These should be arranged in multiple units or increments of capacity to meet partial and minimum load requirements without short cycling.

Chilled water systems 700 kW (200 TR) or less - minimum of 2 chiller units
Above 700 kW to 4218 kW (1200 TR) - minimum of 3 chiller units
Above 4218 kW to 8787 kW (2500 TR) - minimum of 4 chiller units
Above 8787 kW - depends on the good judgment of the design engineer

6.3.3 Considerations should be given at the design stage for providing centralized monitoring and control to achieve optimum operation with minimum consumption of energy.

6.4 Fan System Design Criteria

6.4.1 General

The following design criteria apply to all air conditioning fan systems used for comfort ventilating and/or air conditioning. For the purpose of this Section, the energy demand of a fan system is the sum of the demand of all fans which are required to operate at design conditions to supply air from the cooling source to the conditioned space(s) or exhaust it to the outdoors.

Exception:

Systems with a total fan motor power requirement of 7.5 kW or less.

6.4.2 Constant Volume Fan Systems

For fan systems that provide a constant air volume whenever the fans are operating, the power required by the motors of the combined fan system at design conditions shall not exceed 0.5 $W/m^3/hr$.

6.4.3 Variable Air Volume (VAV) Fan Systems

6.4.3.1 For fan systems that are able to vary system air volume automatically as a function of load, the power required by the motors of the combined fan system at design conditions shall not exceed 0.75 $W/m^3/hr$.

6.4.3.2 Individual VAV fans with motors rated at 7.5 kW and larger shall include controls and devices necessary to make the fan motor operate efficiently even at flow rates of as low as 40% of the rated flow.

6.5 Pumping System Design Criteria

6.5.1 General

The following design criteria apply to all pumping systems used for comfort air conditioning. For purposes of this Section, the energy demand of a pumping system is the sum of the demand of all pumps that are required to operate at design conditions to supply fluid from the cooling source to the conditioned space(s) or heat transfer device(s) and return it back to the source.

Exception:

Systems with total pump motor power requirement of 7.5 kW or less.

6.5.2 Pressure Drop

Chilled water and cooling water circuits of air conditioning systems shall be designed at a maximum velocity of 1.2 m/s for a 51 mm diameter pipe and a pressure drop limit of 39.2 kPa per 100 equivalent m for piping over 51 mm diameter. To minimize erosion for the attainment of the piping system, the following water velocities should not be exceeded:

Table 6.2 MAXIMUM WATER VELOCITY TO MINIMIZE EROSION

Normal Operation (hours per year)	Water Velocity (fps)	(m/s)
1500	10	3.1
2000	9.5	2.9
3000	9	2.7
4000	8	2.4
6000	7	2.1
8000	6	1.8

Note: The noise criteria is not included anymore since noise in piping systems is usually caused by entrained air which could be eliminated.

6.5.3 Variable Flow

Pumping systems that are provided with control valves designed to modulate or step open or close, depending on the load, shall be required for variable fluid flow. The system shall be capable of reducing system flow to 50% of the design flow or less.

Flow may be varied using variable speed driven pumps, multiple stage pumps or pumps riding their performance characteristic curves. Pumps with steep performance curves shall not be used since they tend to limit system flow rates. Variable speed or staged pumping should be employed in large pumping systems.

Exception:

1. Systems where a minimum flow greater than 50% of the design flow rate is required for the proper operation of the equipment served by the system.

2. Systems that serve only one control valve.

6.5.4 Pumping Energy Consumption

The amount of energy used in hydronic systems can be gauged from the Water Transport Factor. This is the ratio of the rate of sensible heat change in the circulating water to power input to all pump mc ors operating in the circulating system, with the heat change measured at the main heat exchange device (e.g., chillers, condensers, etc.).

6.5.4.1 The water transport factor shall not be less than the following values:

Chilled water system	30
Cooling water system (Open or Closed)	50
Hot water system	60

6.5.4.2 For constant volume flow systems, the factor should be based on the design water flow.

6.5.4.3 For variable volume flow, the factor should be based on 75% of the maximum design water flow.

6.6 Air Distribution System Design Criteria

6.6.1 General

6.6.1.1 The temperature and humidity of the air within the conditioned space shall be maintained at an air movement of from 0.20 to 0.30 m/s.

6.6.1.2 The air in such conditioned space(s) should at all times be in constant motion sufficient to maintain a reasonable uniformity of temperature and humidity but shall not cause objectionable draft in any occupied portion(s). In cases wherein the only source of air contamination is the occupant, air movement shall have a velocity of not more than 0.25 m/s as the air enters the space.

6.6.2 Air Distribution

6.6.2.2 Air distribution should be designed for minimum resistance and noise generation. Ductworks should deliver conditioned air to the spaces as directly, quietly and economically as possible and return the air to the cooling source. When the duct layout has few outlets, conventional low velocity design which corresponds to a flow resistance of 0.8 to 1.5 Pa per equivalent m shall be used. In complex systems with long runs and medium to high pressures of 375 to 2000 Pa, ductwork should be designed at pressure drop of not greater than 3 to 5 Pa per equivalent m.

6.6.3 Separate Air Distribution System

6.6.3.1 Areas that are expected to operate non-simultaneously for more than 750 hours per year shall be served by separate air distribution systems. As an alternative, off-hour controls shall be provided in accordance with Section 6.7.3.

6.6.3.2 Areas with special process temperature and/or humidity requirements should be served by air distribution systems separate from those serving the areas requiring only comfort cooling, or shall include supplementary provisions so that the primary systems may be specifically controlled for comfort purposes only.

Exception:

Areas requiring comfort cooling only that are served by a system primarily used for process temperature and humidity control, need not be served by a separate system if the total supply air to these areas is no more than 25% of the total system supply air or the total conditioned area is less than 100 m^2.

6.6.3.3 Separate air distribution systems should be considered for areas having substantially different cooling characteristics, such as perimeter zones in contrast to interior zones.

6.7 Controls

6.7.1 System Control

6.7.1.1 Each air-conditioned system shall be provided with at least one control device for the regulation of temperature.

6.7.1.2 All mechanical ventilation system (supply and exhaust) equipment either operating continuously or not shall be provided with readily accessible manual and/or automatic controls or other means of volume reduction, or shut-off when ventilation is not required.

6.7.2 Zone Control

6.7.2.1 Each air-conditioned zone shall be controlled by individual thermostatic controls responding to temperature within the zone.

6.7.2.2 Systems that serve zones that can be expected to operate non-simultaneously for more than 750 hours per year (i.e., approximately 3 hours per day on a 5 day per week basis) shall include isolation devices and controls to shut off the supply of conditioned air to each zone independently. Isolation is not required for zones expected to operate continuously.

Exception:

1. Systems which are restricted by process requirements such as combustion air intakes.

2. Gravity and other non-electrical ventilation system may be controlled by readily accessible manual damper.

6.7.3 Control Area

6.7.3.1 The supply of conditioned air to each zone/area should be controlled by individual control device responding to the average temperature within the zone. Each controlled zone shall not exceed 465m^2 in area.

6.7.3.2 For buildings where occupancy patterns are not known at the time of system design, such as speculative buildings, isolation areas may be predesigned.

6.7.3.3 Zones may be grouped into a single isolation area provided the to conditioned floor area does not exceed 465 m^2 per group nor clude more than one floor.

6.7.4 Temperature Controls

Where used to control comfort cooling, temperature controllers sho be capable of being set locally or remotely by adjustment or selecti of sensors, between 23°C and 27°C or in accordance with lo regulations.

6.7.5 Location

Thermostats in controlled zones should be located where they me sure a condition representative of the whole space and where they a not affected by direct radiation, drafts, or abnormal thermal conducti or stratification.

6.8 Piping Insulation

6.8.1 All chilled water pipings shall be thermally insulated in accordance w Table 6.3 to prevent heat gain and avoid sweating on the insulati surface. The insulation shall be suitably protected from damage.

6.8.2 Chiller surfaces especially the evaporator shell and compressor su tion line(s) should be insulated to prevent sweating and heat ga Insulation covering surfaces on which moisture can condense or tho exposed to ambient conditions must be vapor-sealed to prevent a moisture seepage through the insulation or to prevent condensation the insulation.

Exception:

1. Piping that convey fluids that have not been cooled through the u of fossil fuels or electricity.

2. Piping at fluid temperatures between 20°C and 40°C.

3. When the heat gain of the piping without insulation does not crease the energy requirements of the building.

Table 6.3 MINIMUM INSULATION THICKNESS FOR VARIOUS PIPE SIZES

Piping System Types	Fluid Temp. Range (°C)	PIPE SIZES (mm) Condensate drains to 50	50 or less	63 to 76	89 ar larg
Chilled Water	4.5 to 13.0	25	38	38	50
Refrigerant or Brine	4.5 and below	50	50	63	63

Note: Insulation thicknesses (mm) in Table 6.3 are based on insulation havi thermal resistivity in the range of 0.028 to 0.032 m^2-°C/W-mm on flat surface at a mean temperature of 24°C. Minimum insulatio thickness shall be increased for materials having R values less tha 0.028 m^2-°C/W-mm or may be reduced for materials having R valu greater than 0.028 m^2-°C/W-mm.

6.8.3 For materials with thermal resistance greater than 0.032 m^2-°C/W-mr the minimum insulation thickness shall be:

$$t = \frac{0.032 \times \text{thickness in Table 6.3}}{\text{Actual R value}}$$

[Equation 6.

where: t = minimum thickness, mm
R = actual thermal resistance, m^2-°C/W-mm

6.8.4 For materials with thermal resistance lower than 0.028 m2-oC/W-mr the minimum insulation thickness shall be:

$$t = \frac{0.028 \times \text{thickness in Table 6.3}}{\text{Actual R value}}$$

[Equation 6.

where: t = minimum thickness, mm
R = actual thermal resistance, m^2-°C/W-mm

6.9 Air Handling System Insulation

6.9.1 All air handling ducts and plenums installed as part of the air distributio system and which are outside of air-conditioned spaces shall b thermally insulated sufficiently to minimize temperature rise of the a stream within them and to prevent surface condensation.

Insulated ducts located outside of buildings shall be jacketed f raintightness and for protection against damage.

Air ducts or plenums within air-conditioned spaces may not be ins lated if the temperature difference, TD, between the air outside ar within the ducts or plenums would not cause surface condensatio Due consideration should be paid to the relative humidity of air su rounding the ducts or plenums.

The required insulation thickness shall be computed using insulatio material having resistivity ranging from 0.023 to 0.056 m^2-°C/W-m and the following equation:

$$L = \frac{kR_s(D_p - t_o)}{(D_b - D_p)}$$

where: D_b = ambient still air dry bulb temperature, °C
D_p = dew point, °C
t_o = operating temperature, °C
R_s = surface thermal resistance
= 0.115 m^2-°C/W
k = mean thermal conductivity, W-mm/m^2-°C
L = thickness, mm

Exception:
1. When the heat gain of the ducts, without insulation, will not increase the energy requirements of the building.
2. Exhaust air ducts

.9.2 The thermal resistance of the insulation, excluding film resistances, should be:

$$R = \frac{TD}{347} \ m^2\text{-°C/W-mm} \qquad \text{(Equation 6.3)}$$

where TD is in °C.

.10 Air Conditioning Equipment

.10.1 Minimum Equipment Performance

Air conditioning equipment shall have a minimum performance corresponding to the rated conditions shown in Table 6.4. Data furnished by equipment supplier or manufacturer or certified under a nationally recognized certification program or rating procedure shall be acceptable to satisfy these requirements.

able 6.4 STANDARD RATED CONDITIONS FOR AIR CONDITIONING SYSTEMS

tream	Water Cooled Water Chillers (°C)	Air Cooled Water Chillers (°C)	Water Cooled Package A/C Units (°C)
hilled Water Supply	7.0	7.0	-
hilled Water Return	12.0	12.0	-
ooling Water Supply	29.5	-	29.5
ooling Water Return	35.0		35.0
ondenser Air Inlet	-	35.0	-
vaporator Inlet	-	-	27.0 DBT (*) 19.0 WBT (**)

lote: (*) Dry Bulb Temperature
(**) Wet Bulb Temperature

.10.1.1 Coefficient of Performance (COP)

The COP of an air conditioning system is the ratio of the useful cooling effect to the total energy input. The total energy input refers to the combination of the energy inputs of all elements of the equipment, including but not limited to: compressor(s), pump(s), fan(s), cooling tower(s) and control(s).

.10.1.2 Unitary Air Conditioning Units - Electrically Operated

This section applies to, but not necessarily limited to, room air conditioners, package air conditioners, direct expansion units and in general, all unitary equipment.

The COP shall not be less than those quoted in Table 6.5.

.10.1.3 Water Chillers - Electrically Operated

This section applies to, but not necessarily limited to, individual components forming part of a system and which are not installed as part of a supplier's matched or complete system.

The COP at design full load shall not be less than the values shown in Table 6.5.

Table 6.5 MINIMUM PERFORMANCE RATING OF VARIOUS AIR CONDITIONING EQUIPMENT

Air Conditioning Equipment	kW_e/kW_r	COP
Unitary A/C units		
Up to 20 kW_r capacity	0.56	1.80
21 too 60 kW_r capacity	0.53	1.90
61 to 120 kW_r capacity	0.50	2.00
Over 120 kW_r capacity	0.48	2.10
Centrifugal chillers (up to 800 kW_r)		
air cooled	0.44	2.30
water cooled	0.25	4.00
Reciprocating chillers (up to 120 kW_r)		
air cooled	0.39	2.60
water cooled	0.26	3.85
Centrifugal chillers (above 800 kW_r)		
air cooled	0.37	2.70
water cooled	0.22	4.54
Reciprocating chillers (above 120 kW_r)		

Notes: kW_e/kW_r = kilowatt electricity per kilowatt refrigeration
kW_e/TR = kilowatt electricity per ton of refrigeration
1 TR = 3.51685 kW_r
Table 6.5 should be in conformity with Table 6.4.

6.10.2 Field-assembled Equipment and Components

6.10.2.1 When components from more than one supplier are used as parts of the air conditioning system, component efficiencies shall be specified based on the data provided by the suppliers/manufacturers, which shall provide a system that complies with the requirements of Section 6.10.1.

6.10.2.2 Total on-site energy input to the equipment shall be determined by the energy inputs to all components such as compressor(s), pump(s), fan(s), purge device(s), lubrication accessories and controls.

6.10.3 Air Conditioning Equipment Controls

Evaporator coil frosting and excessive compressor cycling at part load conditions should be controlled by limited and regulated cycling of the refrigerant rather than by the use of higher hot gas by-pass or evaporator pressure regulator control.

Section 7.0 STEAM AND HOT WATER SYSTEMS

7.1 Scope

This section applies to the energy conserving design of steam and hot water services in buildings such as hotels and hospitals. The purpose of this section is to provide criteria for design and equipment selection that will provide energy savings when applied to steam and hot water systems.

7.2 System Design and Sizing

7.2.1 In large scale schemes, a choice has to be made between central storage of hot water with a circulating loop and individual storage heaters placed locally at demand centers. The system with the lowest overall energy usage (considering the heat losses in the calorifier and the circulating loop of a centralized system and the total heat losses from a system of individual storage heaters) should be chosen.

7.2.2 Service water heating system design loads for the purpose of sizing shall be determined using the procedures given in the latest edition of the ASHRAE Handbook on HVAC Systems and Applications or other equivalent publications.

7.2.3 In systems where boilers are used both for hot water service and other heating applications (steam systems), the boiler capacity should be based on the total heat demand of the hot water system, as calculated in accordance with Section 7.1.2; the expected maximum steam consumption of all installed steam heated equipment, as furnished by the equipment supplier or manufacturer or certified under a nationally recognized certification program or rating procedure; and other miscellaneous loads such as the heat required to initially heat up the water in the system and the heat losses in the steam distribution system.

7.3 Minimum Equipment Efficiency

All boilers and hot water storage tanks shall meet the criteria in Table 7.1.

Exception:
Hot water storage tanks having more than 2 m^3 of storage capacity need not meet the standby loss or heat loss requirements of Table 7.1 if the tank surface is thermally insulated with a suitable insulating material with R = 0.045 m^2-°C/W-mm.

Table 7.1 MINIMUM PERFORMANCE RATINGS OF STEAM AND HOT WATER SYSTEMS EQUIPMENT

Equipment	Minimum Criteria
Shell Boiler (light oil fired)	
@ Rated Capacity	85% boiler eff.
@ Part Load Capacity	80% boiler eff.
Shell Boiler (heavy oil fired)	
@ Rated Capacity	85% boiler eff.
@ Part Load Capacity	80% boiler eff.
Unfired Storage Tanks (all volumes)	
Surface Heat Loss (max)	43 W/m^2

7.4 Hot Water Temperature

The maximum hot water supply temperatures shall be as follows:

For washing ,etc.	40°C
Fot hot baths	45°C
For kitchen use	60°C

It is recommended that two separate systems be installed when two different temperatures are required to minimize piping heat losses. This should always be done where the demand at the lower temperature is greater than 25% of the demand at the higher temperature.

7.5 Controls

7.5.1 Hot water systems shall be equipped with effective automatic temperature controls which are capable of holding the water temperature to +/- 3°C of the temperatures set in Sec. 7.4.

7.5.2 Systems designed to maintain usage temperatures in the circulating loop shall be equipped with automatic time switches or other controls that can be set to turn off the system when use of hot water is not required.

7.5.3 Manual controls shall also be provided to override the automatic controls when necessary. Controls shall be accessible to operating personnel.

7.5.4 Controls of Hot Water Conservation

7.5.4.1 Showers in bathrooms shall have outlets which restrict the flow to not more than 0.2 l/s. Lavatories in public areas of buildings shall have taps with controlled flow at a rate not exceeding 0.05 l/s. This applies to both cold and hot water taps when separate taps are used.

7.5.4.2. Single outlet mixing taps with a flow of 0.05 l/s should be used in preference to separate cold and hot water taps.

7.5.4.3 Point-of-use water heaters shall only be considered if their use is guaranteed to reduce energy cost.

7.6 Piping Insulation

7.6.1 Circulating Systems

The insulation of steam, condensate and hot water lines shall conform to the requirements in Table 7.2 or an equivalent level as calculated in accordance with Eqn. 7.1.

$$t_2 = 50.8\, d_o\, [((1+2\, t_1/d_o)\, \exp\, (r_2/r_1)) - 1] \qquad \text{[Equation 7.1]}$$

where: t_2, t_1 = minimum insulation thickness of materials with r_1 and r_2 thermal resistivity, respectively, mm

r_2, r_1 = thermal resistivities, m^2-°C/W-mm

d_o = outside pipe diameter, mm

Subscript 1 refers to values quoted in Table 7.2; subscript 2 refers to values corresponding to alternate insulating material.

Note: The use of asbestos in any portion of the piping system is not allowed.

7.6.2 Non-circulating Systems

The first 2.5 m of outlet piping from a storage system that is maintained at a constant temperature and the inlet pipe between the storage tank and the heat trap shall insulated as provided in Table 7.2 or to an equivalent level as calculated in accordance with Equation. 7.1.

Table 7.2. MINIMUM PIPE INSULATION (HEATING SYSTEMS)

System Types	Fluid Temp. Range (°C)	PIPE SIZES (mm) Runouts to 50	25 or less	31 to 50	63 to 76	89 and larger
Steam and Conden-sates	>180 (a)	38	63	63	76	89
	120-180 (b)	38	50	63	63	89
	95-120 (c)	25	38	50	50	50
	60-35 (d)	12	38	38	38	38
	40-60 (e)	12	25	25	25	38
Hot Water	40 & (e) above)	12	25	25	38	38

Note: Thermal resistivity (m2-oC/W-mm) ranges are as follows:
(a) R = 0.020 - 0.022
(b) R = 0.022-0.024
(c) R = 0.023 - 0.026
(d) R = 0.024 - 0.028
(e) R = 0.025 - 0.029

7.7 Waste Heat Recovery and Utilization

7.7.1 Consideration should be given to the use of condenser heat, waste hea or solar energy to supplement hot water requirements.

7.7.2 Storage should be used to optimize heat recovery when the flow of hea to be recovered is out of phase with the demand for hot water.

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BIBLIOGRAPHY

Acoustical Designing in Architecture	*Vern O. Knodsen* *Cyril M. Harris*
Mechanical and Electrical Equipment for Buildings	*McGuinness* *Stein* *Reynolds*
MIH Living Magazine	*Oct, 1983*
How to Decorate without a Decorator	*Mary Gilliatt*
Brochures from different companies	*Pointer Enterprises, Inc.* *ACI House* *Campos Rueda Inc.* *AVD Marketing Corp.*
Architect's Data	*Ernst Neufert*
Asian building and construction	*March 1974*

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